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FINAL REPORT

BRUSHLESS ROTATING ELECTRICAL GENERATORS FOR SPACE AUXILIARY POWER SYSTEMS

CONTRACT NO. NAS 3-2783

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

by

J. N. Ellis and F. A. Collins

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LEAR SIEGLER, INC.

POWER EQUIPMENT DIVISION

CLEVELAND 1, OHIO

NASA CR-54321

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April 26, 1965

Contract No. NAS 3-2783

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ABSTRACT

29597

This final report on the study of brushless rotating electrical generators for space auxiliary power systems describes eighteen types of brushless A.C. generators and recommends four for aerospace use.

The reader is referred to the Topical Report NASA CR-54320 for the electrical and mechanical analysis methods resulting from the study. The Topical Report consists of five volumes containing 10 design manuals and 9 Fortran computer programs for use in calculating the electrical performance and characteristics of brushless A.C. generators. It contains generator selection aids, a discussion of gas bearings for generators, and a discussion of the problem of critical speeds. The report includes a Fortran computer program for generator thermal analysis plus examples, test data, derivations and discussions. author

Introduction

For power generation in the vacuum of space and for some remote unattended installations, brushes riding on slip rings or commutators cannot be used. In many applications, because of temperature or radiation, semiconductor type rectifiers cannot be used in the rotating machine. For these generating systems brushless, rectifierless generators must be used.

Several generators of the general brushless type of interest today in the aerospace industry were invented and built in the past before there was a necessity for generators to be brushless. Quite a few were conceived during the time around 1900. The wound-pole A.C. brush type generators were also developed about 1900. They were superior in performance to the brushless types so the brushless generators, except for the homopolar inductor A.C. generator, were largely forgotten.

Generators for space power conversion systems should possess the capability of reliably operating at high turbine speeds, be capable of operating at high temperatures, and should be designed to withstand high radiation levels. Some of the old brushless A.C. generators offer the capability of providing these characteristics and many of the old generators have been reinvented or have been rediscovered.

The rotating rectifier A.C. generator is the most important brushless generator both in aerospace and in commercial use so it should be included in any study or discussion of brushless A.C. generators. Since we do include it, the electromagnetic generators might be grouped in classes such as:

1. Rotating coil or wound-rotor A.C. generators using rotating exciters and rectifiers to make them brushless.

2. Stationary-coil generators with the coil inside the rotor diameter.

3. Stationary-coil generators with the coil outside the rotors.

Those A.C. generators discussed in this Final Report are:

Salient-pole, wound-rotor, rotating rectifier generator.

Non-salient pole, wound-rotor, rotating rectifier generator.

Rotating-coil Lundell (automotive type) generator.

Inside, stationary coil Lundell (automotive type) generator.

Inside, stationary, two-coil Lundell (Becky-Robinson Patent) generator.

Two, Outside-coil, Lundell generator.

One, Outside-coil, Lundell generator.

Axial air-gap Lundell generator.

Homopolar inductor A.C. generator.

Permanent-magnet A.C. generator.

Induction generator.

Heteropolar inductors, three types.

Homopolar Lundell generator.

Cascade generator.

Two disk-type homopolar A.C. generator.

The first ten listed are treated in the Topical Report NASA CR-54320.

Even though most or all of the brushless A.C. generators are 60 or 70 years old in concept, they have not been widely used and design procedures for them have been incomplete or not generally known where they existed at all. Perhaps because of the lack of design information, the performance limits of the brushless A.C. generators have not been well understood. As a result, fantastic performance and weight claims have at times been made for nearly all of the generator types studied under this contract.

One purpose of the Topical Report NASA CR-54320 issued under this study contract is to establish a sound technical communication medium for describing brushless A.C. generators.

Another purpose of this investigation is to provide a means of selecting and evaluating generators for specific applications. Other aims are to provide means of calculating generator performance, to provide means of determining generator limitations, and to provide a means of determining the effect of improved materials on the generator performance.

To satisfy the purposes and objectives of the investigation, the investigators have written ten (10) design manuals and nine (9) Fortran computer programs. To calculate operating temperatures of the generators, Mechanical Technology, Inc. of Latham, New York has written in Fortran, for Lear Siegler, a thermal analysis program for small generators. The same company (MTI) has written for this study a discussion on gas bearings and a discussion of rotor dynamic characteristics.

Also included in the topical report are calculation examples, discussions of pole face losses, $\frac{\ell}{d}$ ratios, flux plotting, motor performance and design formulae derivations.

Conclusions

The investigators concluded that the four best generators were:

1. Wound pole generator with rotating rectifier where rotational speeds and temperatures allow its use.

2. The two, inside-coil Lundell or Becky-Robinson generators where speeds and temperatures are too high for the wound-pole generator or where nuclear radiation would damage the solid state rotating rectifiers needed for the wound-pole generator.

3. The outside-coil Lundell generator for extreme temperatures and high speeds but where rotor stresses do not exceed the capabilities of a composite weldment.

4. The homopolar inductor for the most severe environments and the highest speeds.

DISCUSSION OF BRUSHLESS A-C GENERATOR TYPES

The topical report NASA CR-54320 discusses the generators that are treated in the study. Some of that material is repeated here and some machines that were not treated in the study are discussed here.

THE WOUND-POLE, SALIENT-POLE, A.C. GENERATOR

The salient-pole, synchronous generator with wound poles is the standard generator of the electrical industry. It is the standard generator because it has the highest electrical output per pound per rpm of any practical generator yet known. Its reactances are the lowest of any of the generators which means that its regulation and performance under transient load conditions are the best of all the a.c. generators.

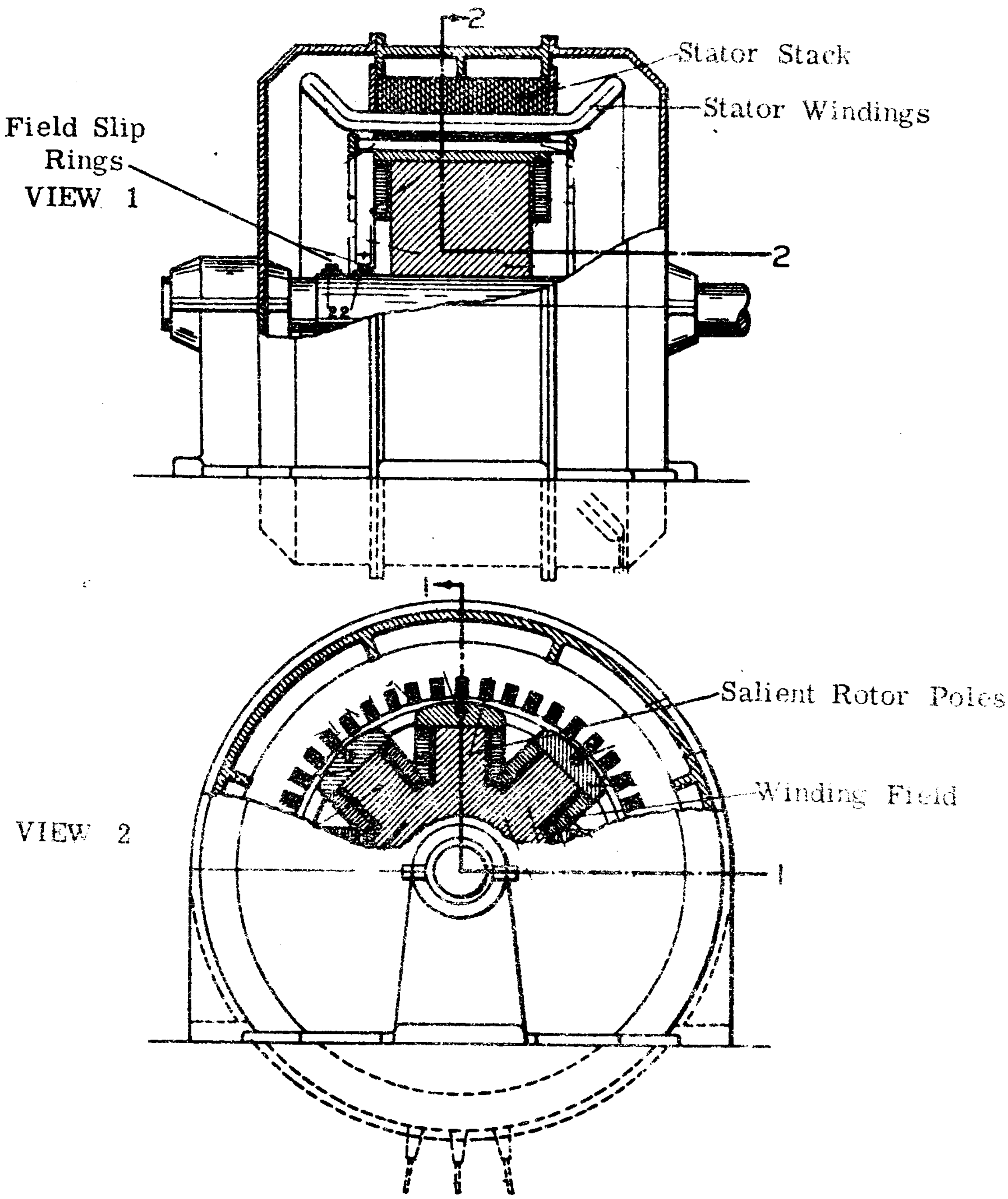
The wound-pole, salient-pole synchronous generator is used on both aircraft and utility systems almost to the exclusion of any other types except non-salient pole, wound rotor, generators (or turbine generators) which are used with 1800 rpm and 3600 rpm steam turbines in central station generating plants.

In addition to its use as an electrical generator, the salient-pole, wound-pole, machine makes the best synchronous motor known. The pole heads can be designed with cage windings so that the machine can start a substantial load as an induction motor. The cage windings can be made double to give good starting characteristics and good pull-in characteristics.

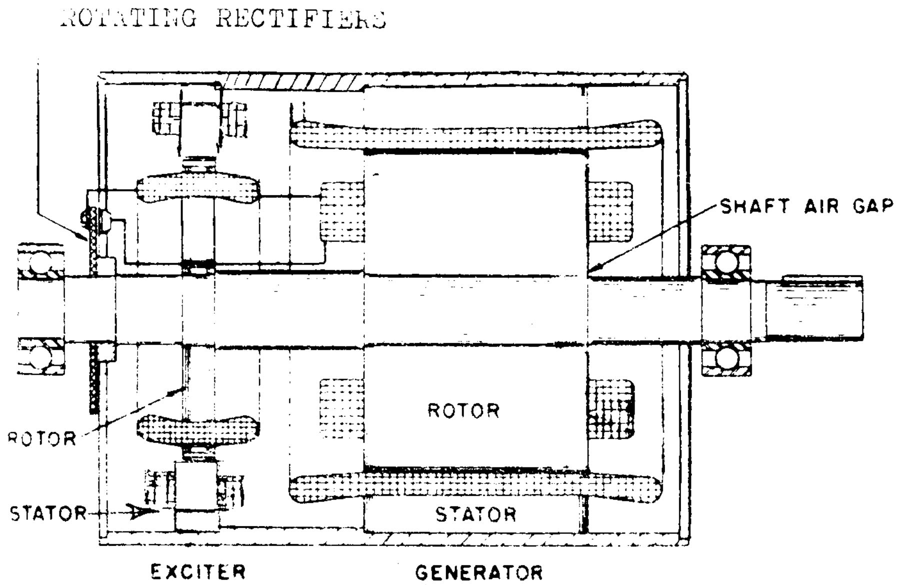
Within its usable range, the wound-pole synchronous generator has no equal, but its range of usefulness is limited. Its maximum rotor peripheral speed is low because the field windings are supported by the poles and high stresses result from the centrifugal loading of the field coils. The maximum output frequency of the generator is low because the possible number of poles is restricted by electrical and mechanical limits imposed by the field windings, pole construction and the need for having at least one slot/phase/pole in the stator. Its maximum operating temperature is about 600° F for the copper and insulation on the rotor and 350° F for the rotating (silicon) rectifiers.

For extreme temperature, high radiation environments and for high peripheral speeds, the rotating-rectifier wound-pole, salient-pole generator is not useable and other more rugged generators are used. The more rugged generators are all heavier, on a KVA per revolution basis, than the wound-pole, salient-pole machines.

Although generators other than the wound-pole, salient-pole synchronous generator are now often used in both aerospace and ground power applications, it is well to remember that within its application range, no other type of a-c generator can compare with the wound-pole, salient-pole machine and it should be used whenever feasible.

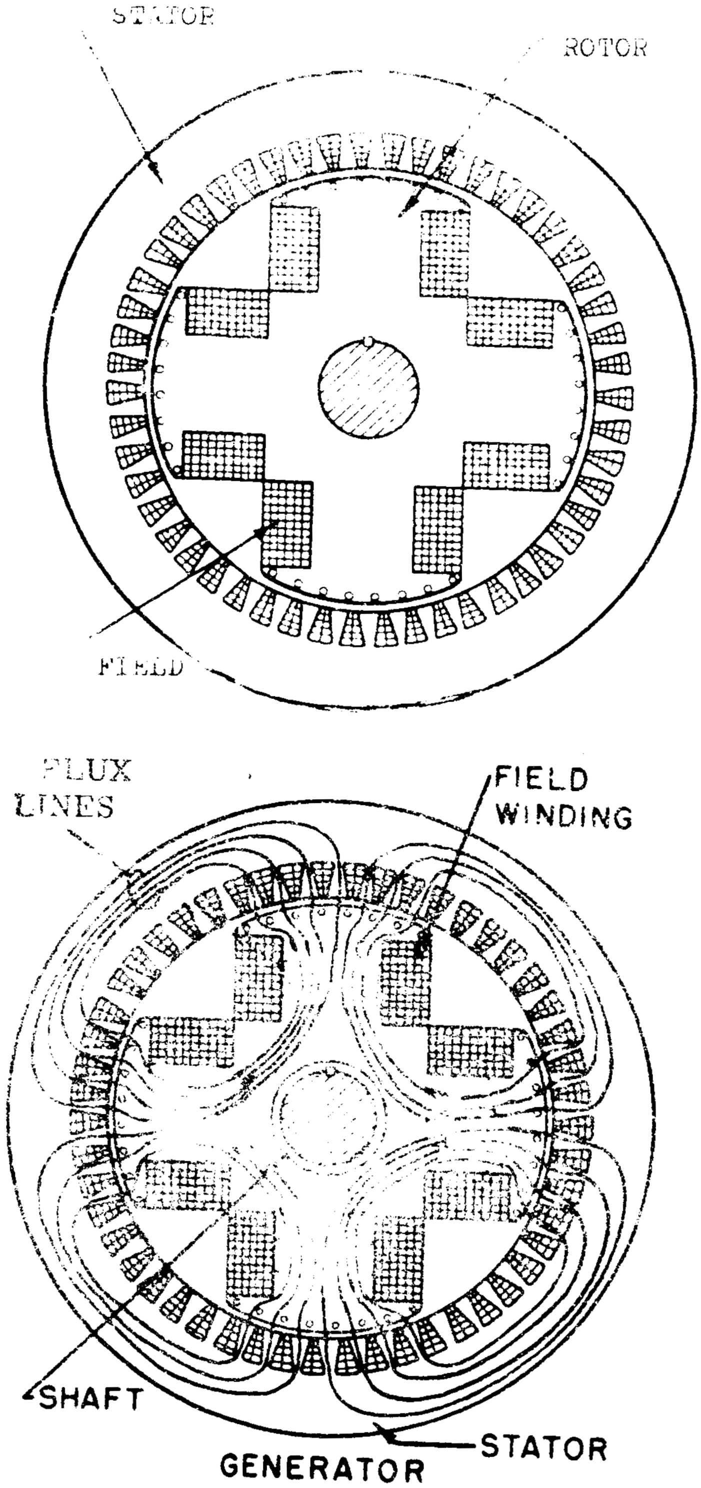


TWO VIEWS OF A WOUND-POLE, SYNCHRONOUS GENERATOR THAT USES SLIP-RINGS TO CONVEY THE EXCITATION CURRENT TO THE FIELD WINDINGS



A-C Generator

SCHEMATIC SHOWING THE ARRANGEMENT USED TO MAKE THE WOUND-POLE GENERATORS BRUSHLESS. THE A-C CURRENT IN THE EXCITER ROTOR IS RECTIFIED BY THE ROTATING RECTIFIERS AND THE D-C OUTPUT OF THE RECTIFIERS IS FED INTO THE MAIN GENERATOR FIELD WINDINGS



SECTION VIEWS OF A WOUND-POLE, SYNCHRONOUS GENERATOR SHOWING THE ARRANGEMENT OF THE WINDINGS AND THE PATH OF THE MAGNETIC FLUX

WOUND-POLE, NON-SALIENT-POLE A.C. GENERATOR

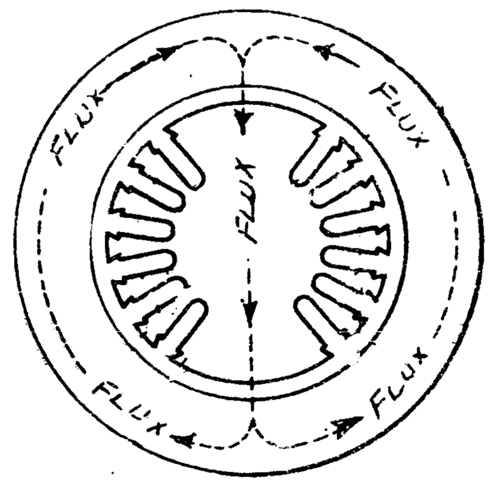
The non-salient pole or round-rotor A. C. generator is widely used in central station power plants where the generator is coupled to a steam turbine and operated at 1800 rpm or 3600 rpm. Because its pole windings are contained in slots in the rotor, this generator is capable of higher peripheral speeds than are possible with the salient pole wound-pole generator.

Several 8000 rpm and 12000 rpm generators have been built as non-salient wound-rotor machines for aircraft and auxiliary power where wound-pole salient-pole generators could not be used for the ratings and speeds desired.

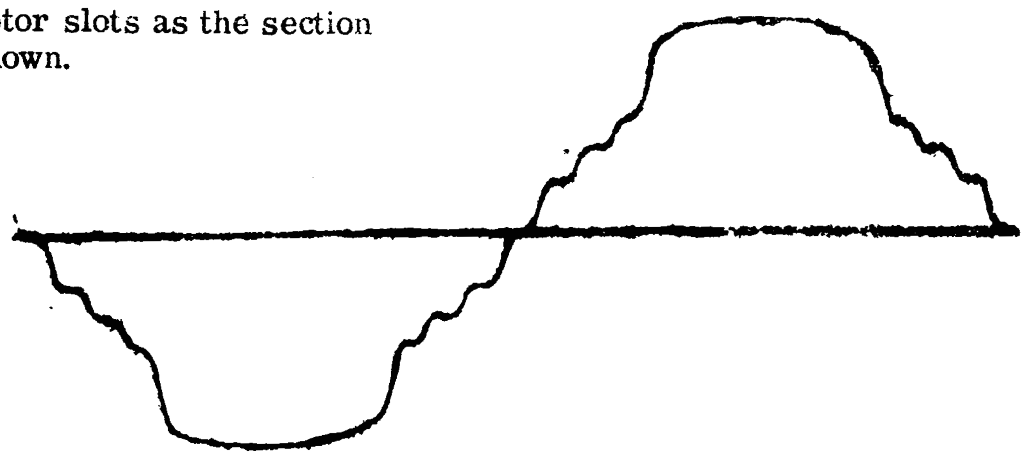
When two-pole, wound-pole generators are built, they are usually non-salient pole machines because the rotor construction of the non-salient generator is stronger and more practical than that of a two-pole, salient-pole generator.

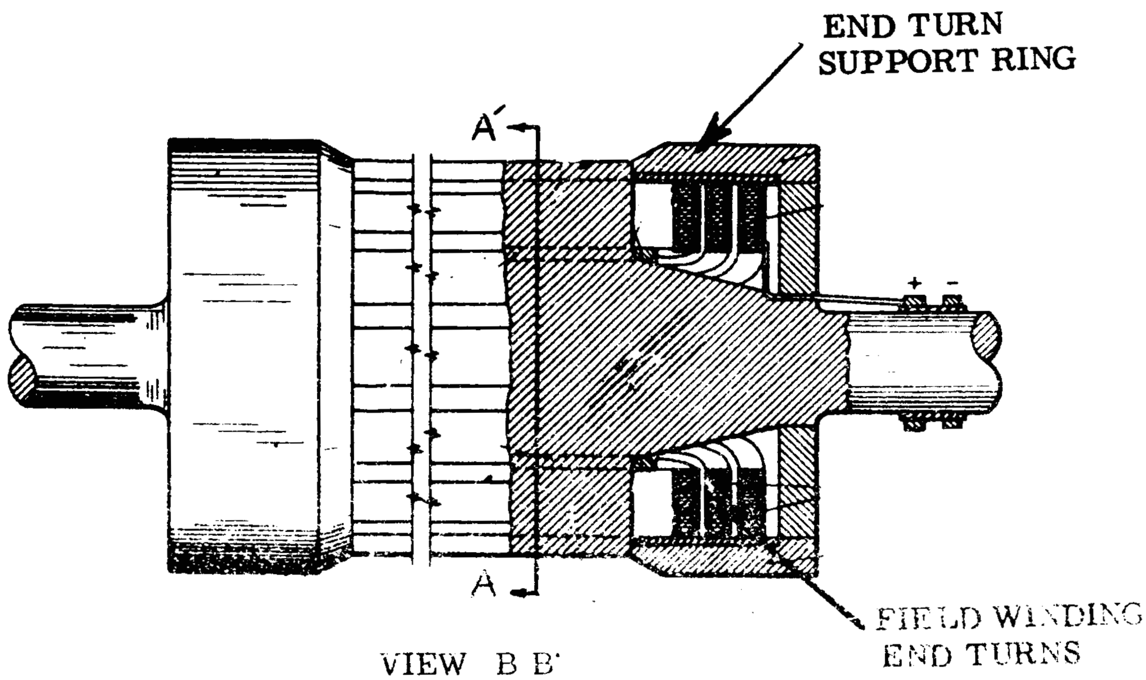
The wound-rotor, non-salient pole electrical generator is a good machine to use in mild environments when the peripheral speeds are too high for the salient-pole wound-pole generator, but not so high that the rotor winding creeps and allows the rotor to change balance.

A section of a two-pole, non-salient-pole rotor without its field winding and a field form of a similar rotor.



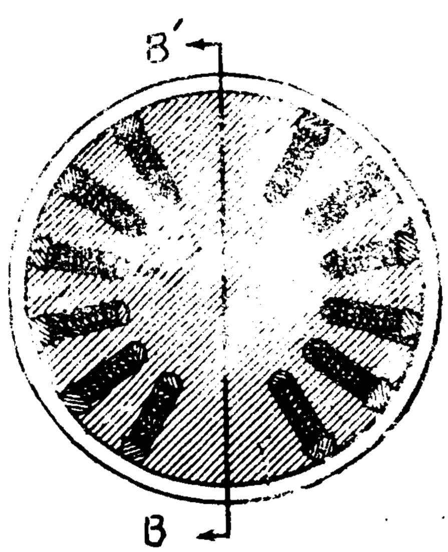
The field form was made with an oscillograph and a search coil. The rotor represented by the record had the same number of rotor slots as the section shown.





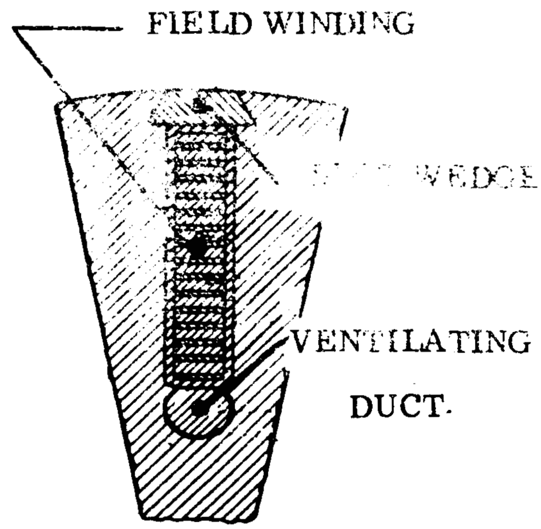
VIEW B B'

ROTOR OF NON-SALIENT-POLE
SYNCHRONOUS A-C GENERATOR



SECTION A A'

CROSS-SECTION OF ROTOR



SECTION VIEW OF SLOT
AND FIELD WINDING

INSIDE-COIL, ROTATING-COIL LUNDELL A.C. GENERATOR

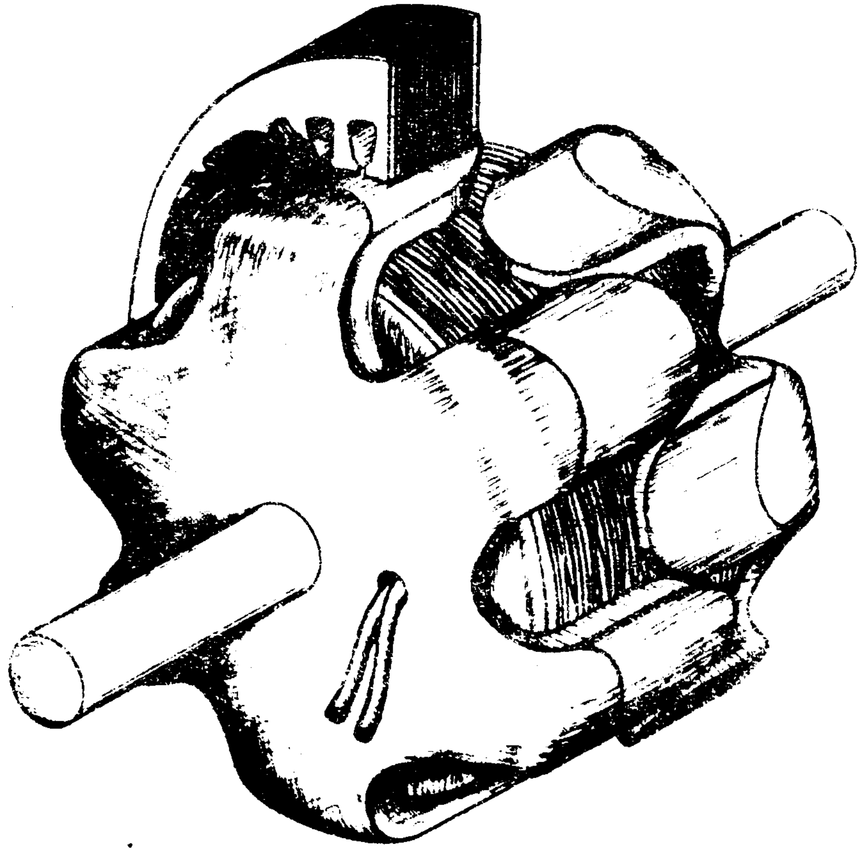
The Lundell generator with a rotating excitation coil is the a. c. generator that has been used for years on automobiles, trucks and busses. To make this generator brushless, an exciter and rotating rectifiers must be used.

The rotating-coil Lundell a. c. generator is limited to the same temperatures and radiation environments that the wound-pole generators are capable of withstanding. It is of interest in this study because it is a basic generator type and can be considered a transition step or link between the so-called solid-rotor brushless generators and the wound-pole, rotating-rectifier, brushless generators.

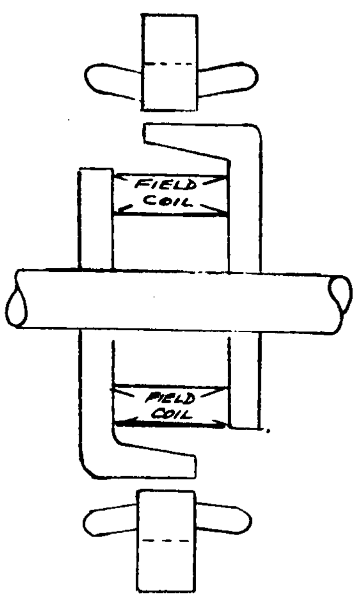
The following discussion will help the reader to understand the basic similarities and differences of various machine types in this report. By showing how one type of machine can be transformed to another type, the reader can see the electromagnetic relationships existing among these machine types. An understanding of these relationships may make it easier for the reader to follow the analytical steps described in the design manuals.

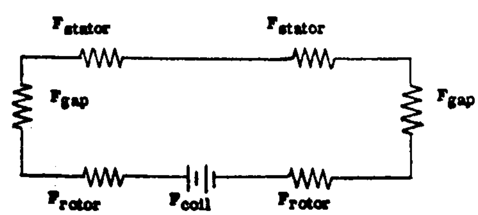
ROTATING COIL

LUNDELL A-C GENERATOR



To show how the rotating-coil Lundell a. c. generator can be made into an outside-coil brushless a. c. generator, take the basic generator below:

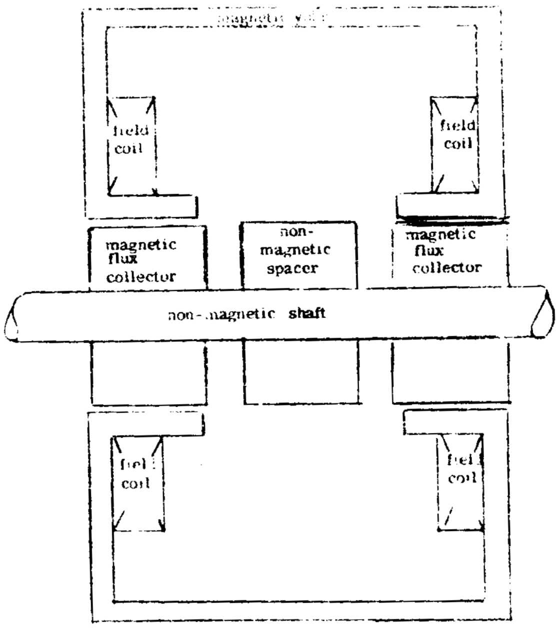




STEP 1

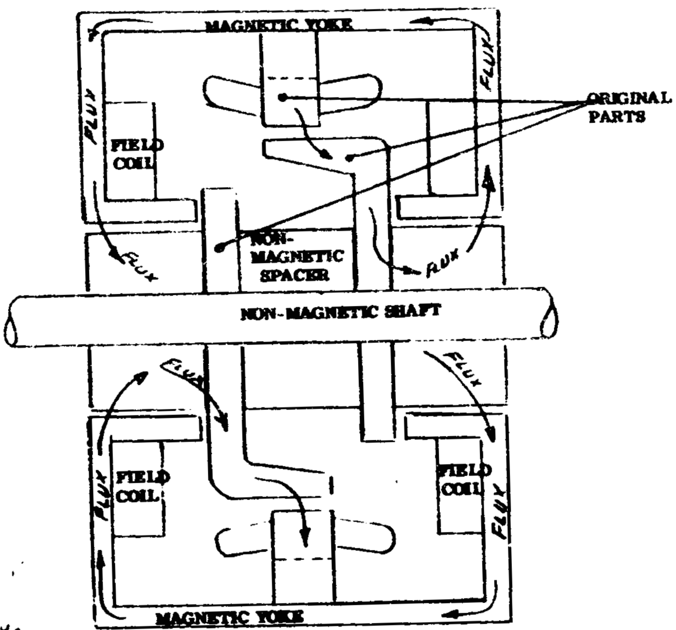
REMOVE THE FIELD COIL AND ADD THESE PARTS

TO MAKE THE GENERATOR SHOWN BELOW AS STEP 3

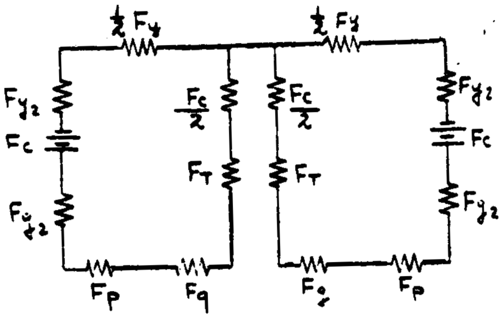


STEP 2

THE RESULT IS A TWO-COIL, OUTSIDE-COIL BRUSHLESS, LUNDELL, A-C GENERATOR SIMILAR TO THAT PATENTED BY L. C. RICE IN 1897.

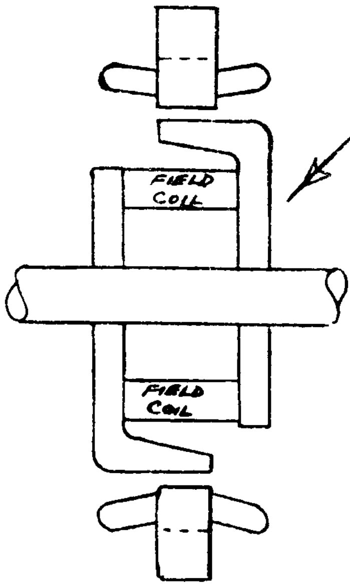


STEP 3



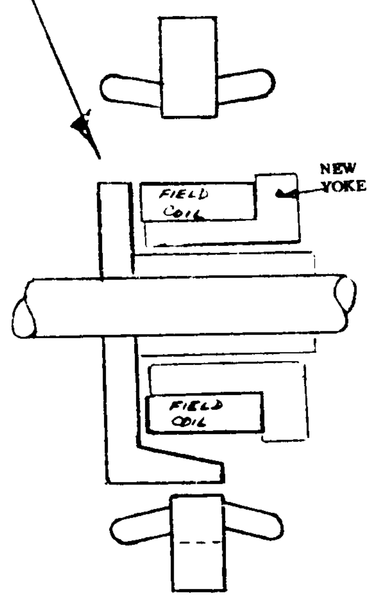
HOW TO MAKE AN INSIDE, SINGLE, STATIONARY-COIL LUNDELL BRUSHLESS, A-C GENERATOR OUT OF A ROTATING-COIL A-C GENERATOR

Using the basic rotating-coil parts, STEP 1,



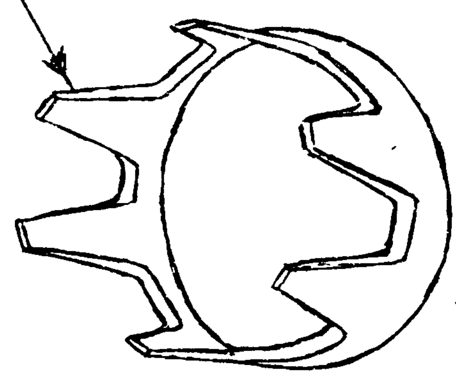
STEP 1

remove one pole-carrying flux plate. Modify the center shaft to allow the field coil to remain stationary, and to provide an auxiliary air-gap at the shaft surface. The auxiliary gap allows the exciting flux to pass around the field coil. This configuration is shown as STEP 2.

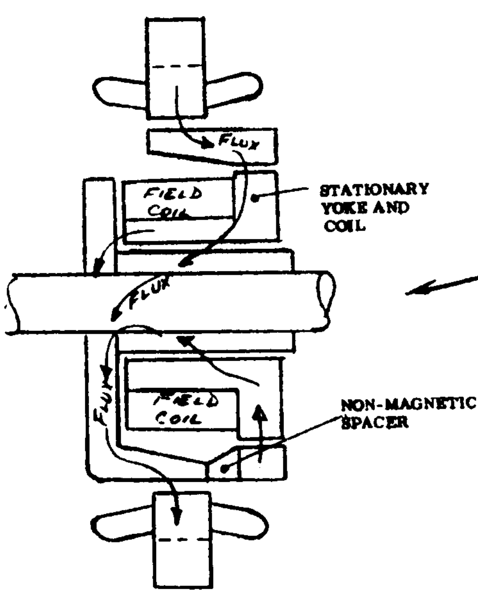


STEP 2

Add the new pole-carrying flux collector ring and fasten with non-magnetic spacers



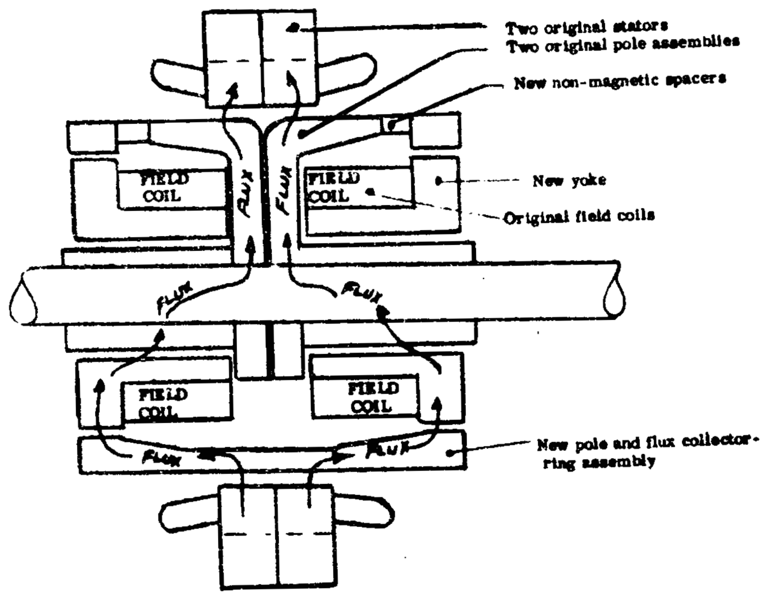
To make the inside, stationary single-coil Lundell shown as STEP 3.



STEP 3

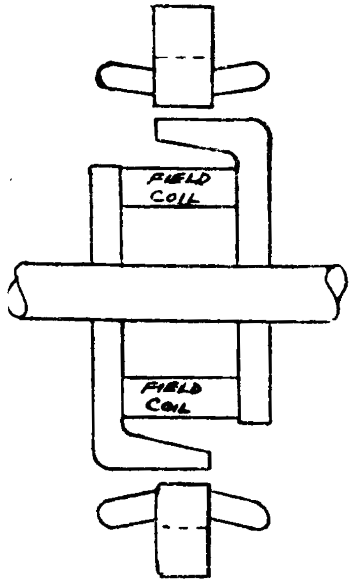
HOW TO MAKE AN INSIDE, STATIONARY, TWO-COIL LUNDELL A-C GENERATOR (BECKY-ROBINSON)

Use two of the inside, single, stationary-coil generators back-to back to make a two, inside, stationary-coil Lundell a-c generator (Becky-Robinson).

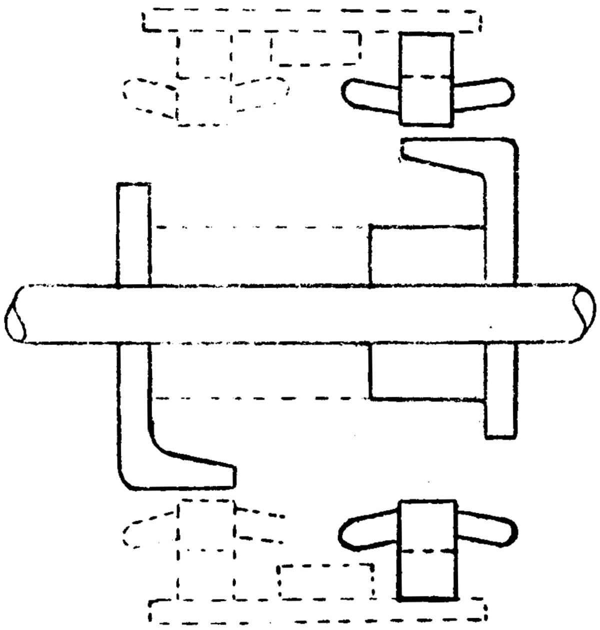


TO MAKE A HOMOPOLAR GENERATOR

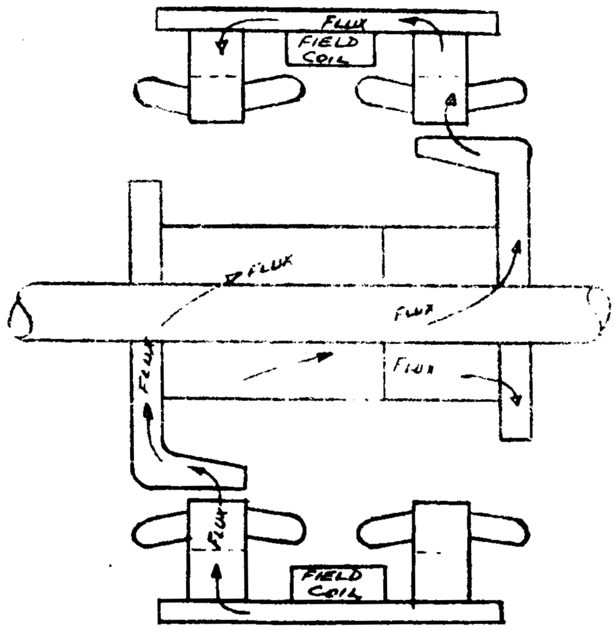
Use the basic rotating coil parts, step 1. Remove the field coil. Separate the rotor parts as shown in step 2, and add the parts shown in phantom to make the complete homopolar inductor shown in step 3.



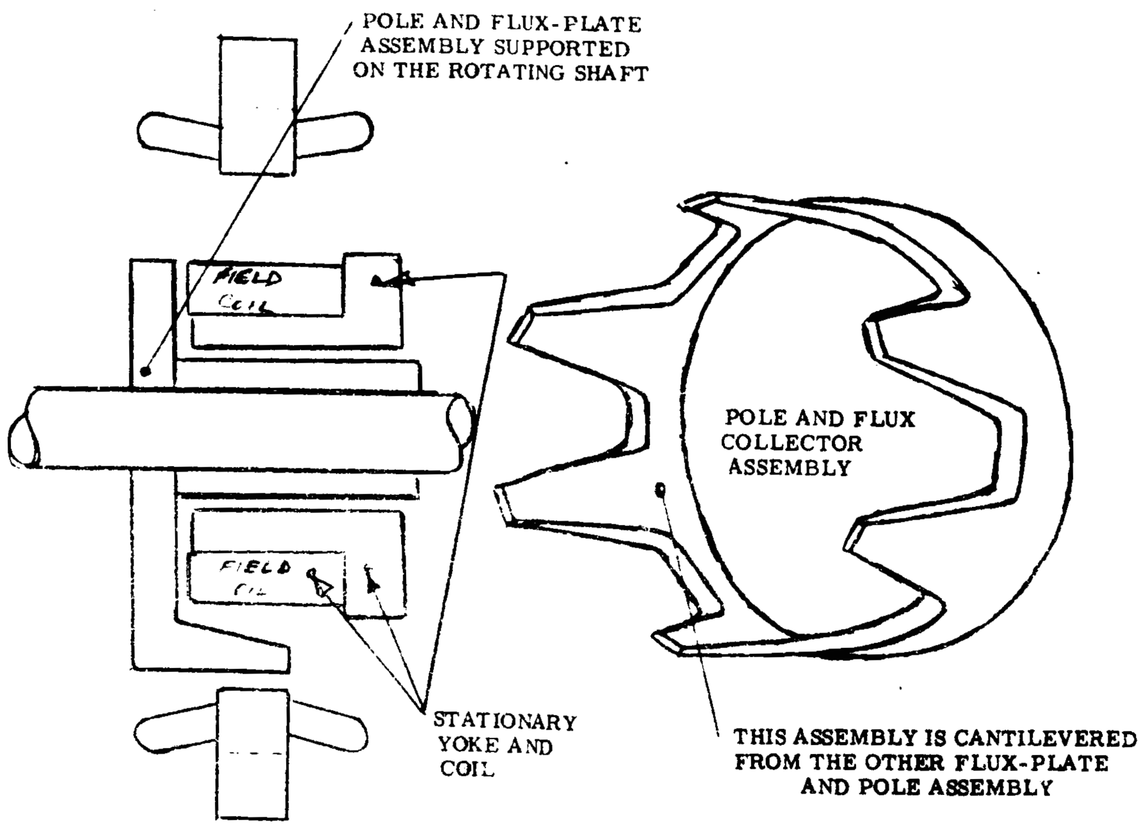
STEP 1

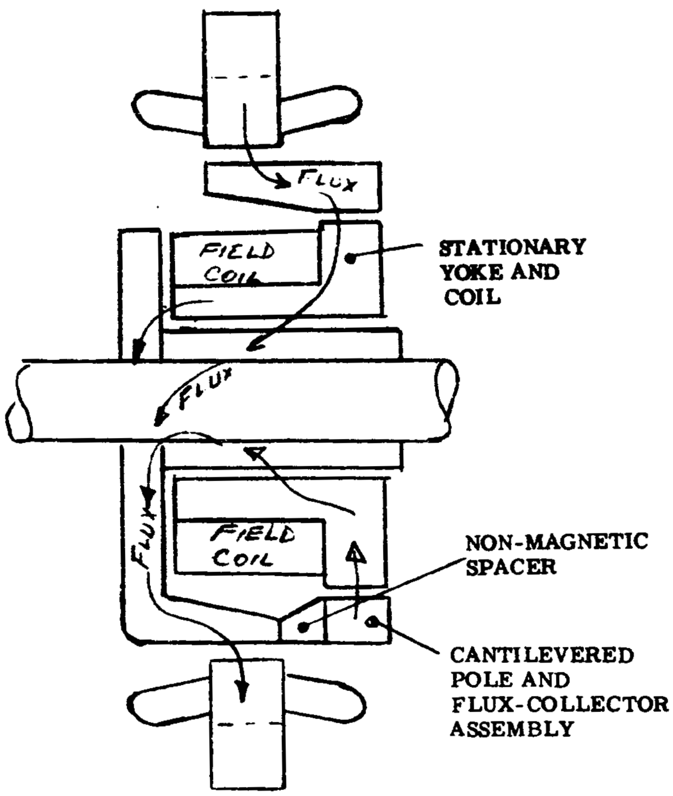


STEP 2



STEP 3





THE GENERATOR SHOWN HERE ABOVE HAS BEARINGS AT EACH END OF THE ROTOR AND THE YOKE AND COIL MUST BE SUPPORTED FROM THE HOUSING OR END-BELL

SINGLE, STATIONARY, INSIDE-COIL LUNDELL GENERATOR

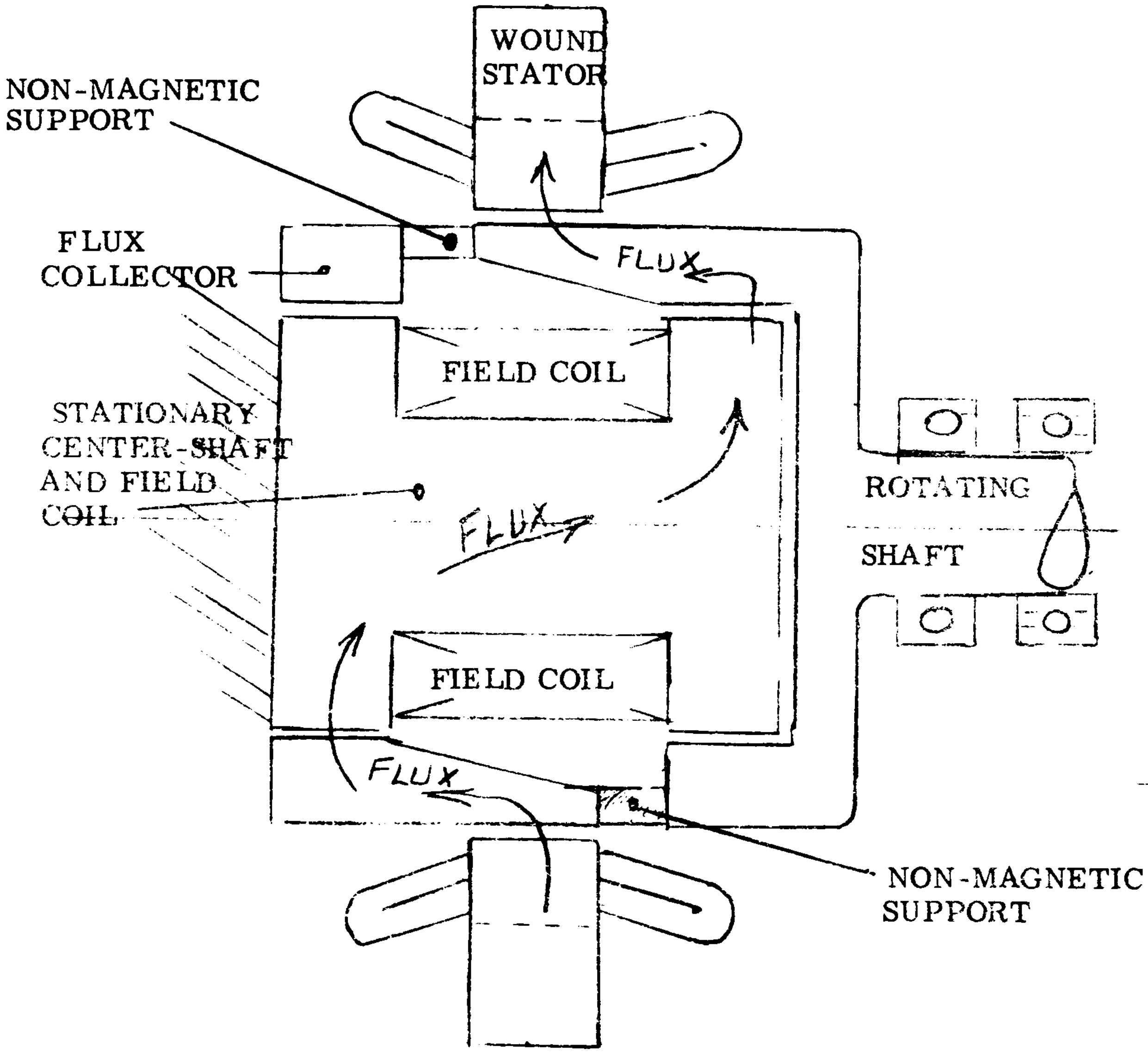
This brushless generator is similar to the rotating-coil Lundell except that it has two auxiliary air-gaps and the excitation coil remains stationary. A flux carrying member rotates above the auxiliary air gap.

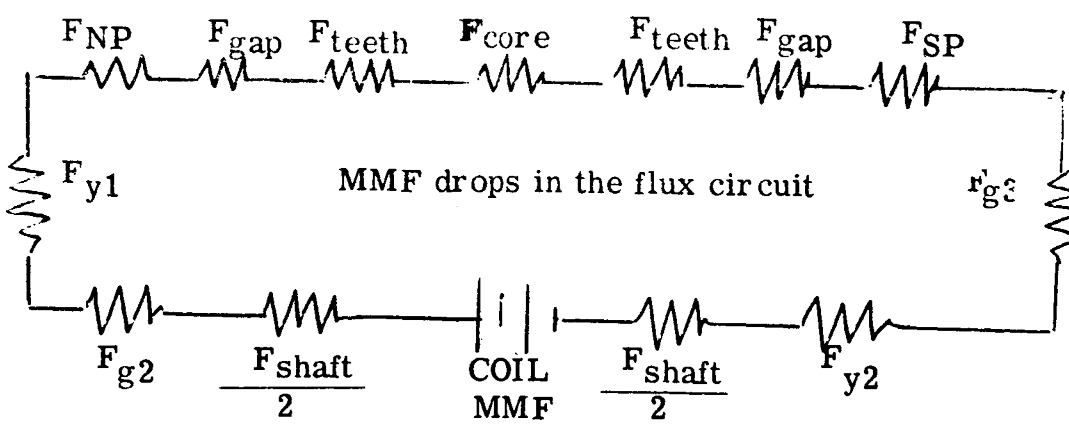
The single, stationary, inside-coil Lundell has been made in this country for several years. Its application has been on trucks, busses and other heavy vehicles requiring a husky, low maintenance electrical power supply.

In the description of the rotating coil Lundell generator, you are shown the steps required to make a rotating coil generator into the stationary-coil type of AC generator. By using two of these single, stationary-coil generators back-to-back, we can make a two, inside, stationary-coil Lundell or Becky-Robinson generator. These demonstrations show the close relationship of all of the Lundell-type generators.

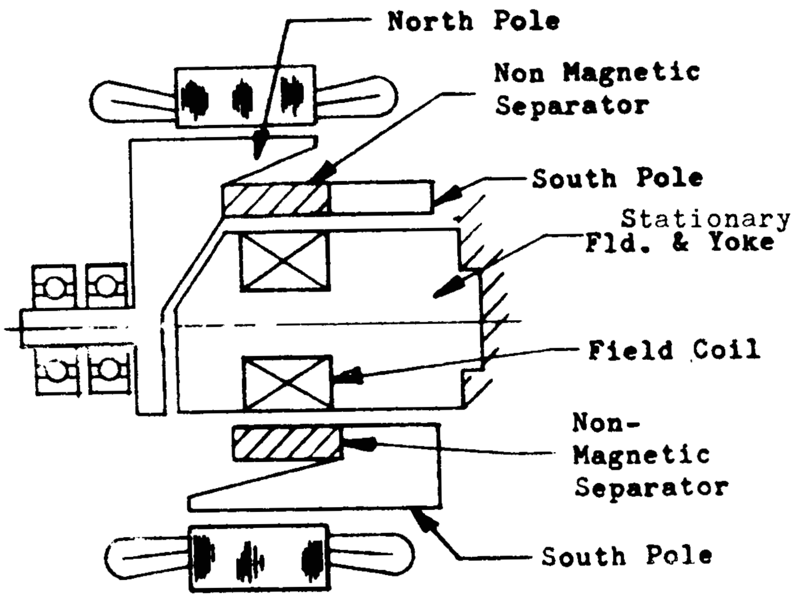
The sketches immediately following show the generator without the over-hung pole and flux collector assembly attached. Another accompanying sketch shows the completely assembled electromagnetic parts for a

A SINGLE, INSIDE, STATIONARY-COIL, LUNDELL, A-C GENERATOR





stationary, single, inside-coil generator with bearings at each end of the rotor.

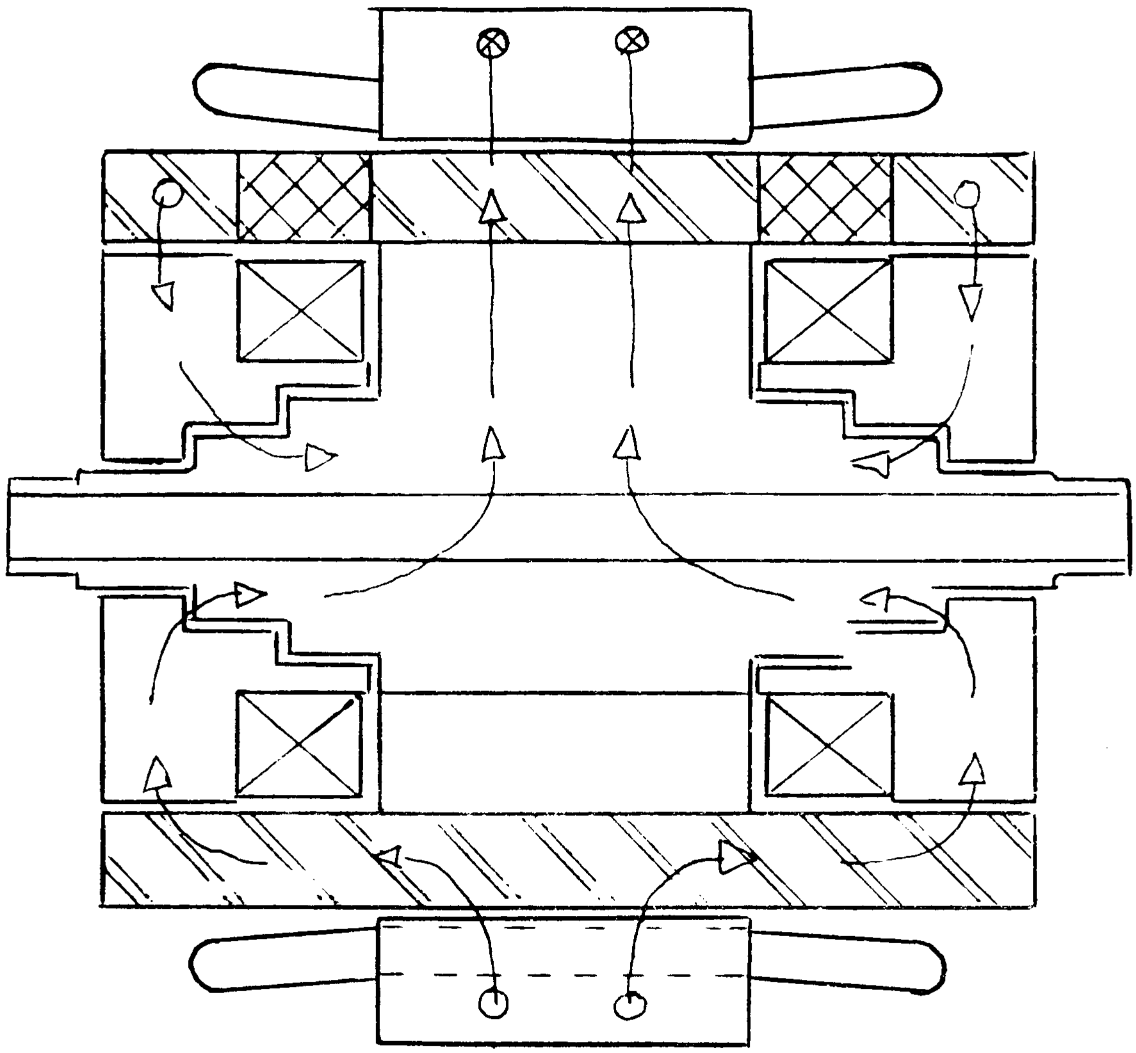


The generator configuration shown above has a coil support cantilevered from the housing and the rotating structure is overhung. The configuration with bearings at each end of the rotor and the one with the overhung rotor are electrically and magnetically equal. The requirements of a specific application might dictate which type is to be used.

This brushless generator can operate successfully at temperatures above the capability of the wound-pole generators. There are no rotating semi-conductors and the stationary excitation coil is not subjected to stress.

The rotational speed is limited by the stresses in the cantilevered pole structure and vibration limits for this generator are lower than those for some of the other generators.

INSIDE-COIL, STATIONARY, TWO-COIL
LUNDELL A. C. GENERATOR (BECKY-ROBINSON)



A brushless, stationary-coil Lundell-type generator that uses two exciting coils is described in U. S. Patent 2,796,542 issued to A. Becky and

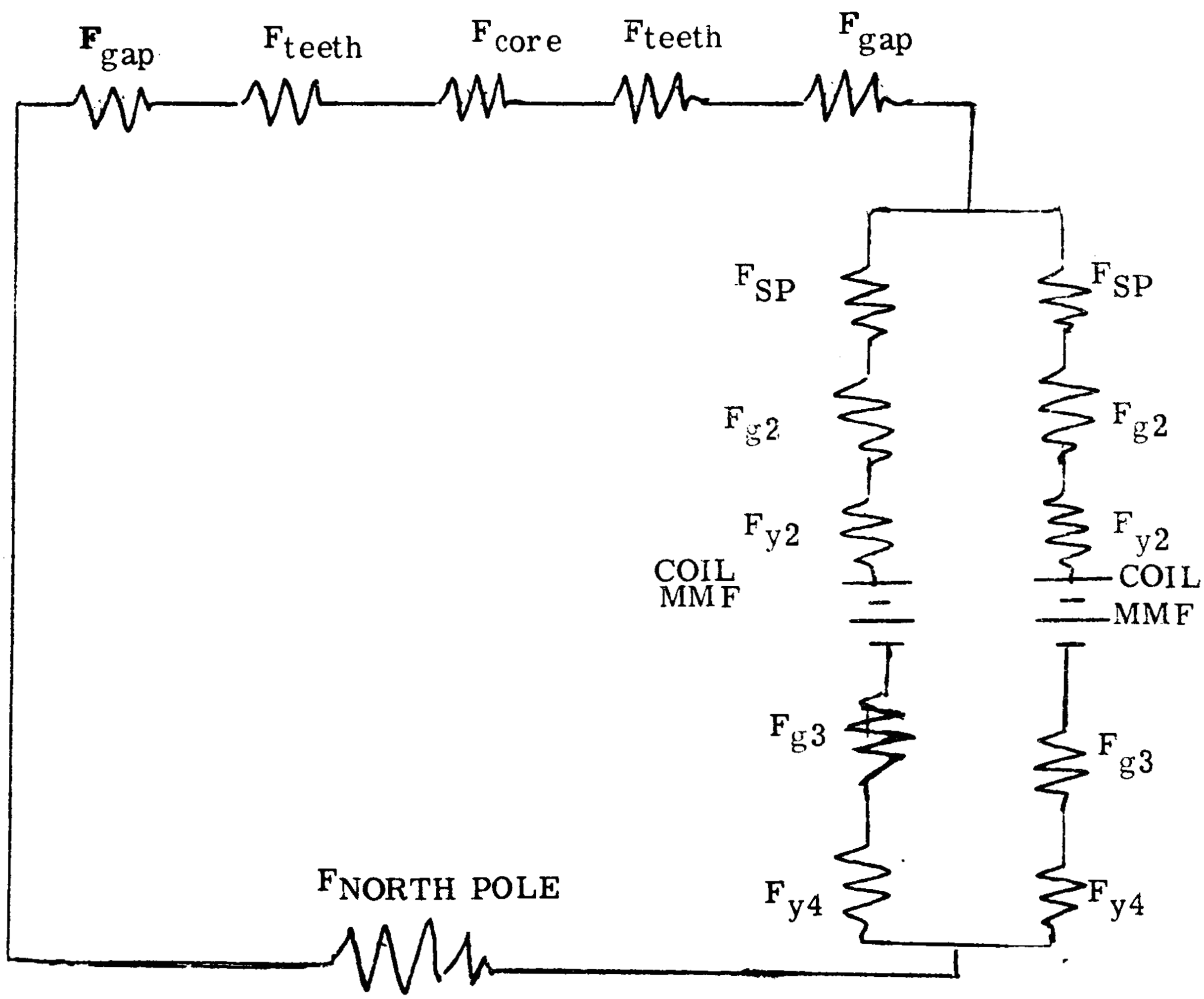
H. M. Robinson. This machine can be thought of, for calculating purposes, as essentially two single, inside, stationary-coil Lundell a. c. generators back-to-back. The description and discussion of rotating-coil Lundell generators explains how the Becky Robinson generator can be evolved from the rotating coil generator by making single stationary coil machines first, then putting two of them together back-to-back.

The Becky-Robinson generator can be made in ratings twice as large for the same stator inside diameter as is possible for the single, inside-coil Lundell, or the rotating coil Lundell. This advantage allows the Becky-Robinson machine to be used in larger ratings and/or at higher rotational speeds than the ratings and speeds of the single coil configuration.

The peripheral speed limits for the two-coil, inside-coil generator are about the same as for the single coil, inside-coil generator. The tolerable speeds are probably a little higher because the Becky-Robinson machine has less overhang on the tube, or pole and flux collector assembly. The environmental limits for the Becky-Robinson generator are tabulated and compared with the other generators in Section B, "Generator Selection Criteria", in the Topical Report NASA CR-54320.

This Becky-Robinson generator is the lightest weight of all of the stationary-coil brushless generators when compared at the same KVA and RPM. It can be used in environments too severe for the wound-rotor generators and its best application area appears now to be auxiliary electrical power generators or system electrical power generators for use in supersonic aircraft when the temperature of the cooling medium is too high for wound-pole generators and semi-conductor rectifiers. The same generator is suitable for ordnance vehicles under the same circumstances - when the wound rotor or rotating coil generators cannot be used because the temperature of the coolant is too high.

The schematic below shows the MMF drops in the flux circuit of a two, inside, stationary-coil Lundell, a-c generator (Becky-Robinson generator).



OUTSIDE-COIL, STATIONARY-COIL LUNDELL A. C. GENERATORS

Two-Coil, Outside-Coil Lundell

The two-coil, outside-coil Lundell a. c. generator and the single-coil outside-coil Lundell a. c. generator are two variations of the same machine. The two coil configuration was patented by Mr. L. C. Rice in 1897.

The two-coil configuration is built by Allgemeine Elktricitate Gesellshaft in Western Germany, by Siemens-Schuckertwerke, Erlangen, Germany, and is used in Russian railway service. It is offered by several U. S. A. companies for aerospace use and is potentially one of the best generators for use in severe environments.

The flux paths through the two-coil version can be represented by the mmf drops shown in Figure A 33. The flux circuit shown in Figure A-33 A is for a machine having its stator iron touching the housing or yoke.

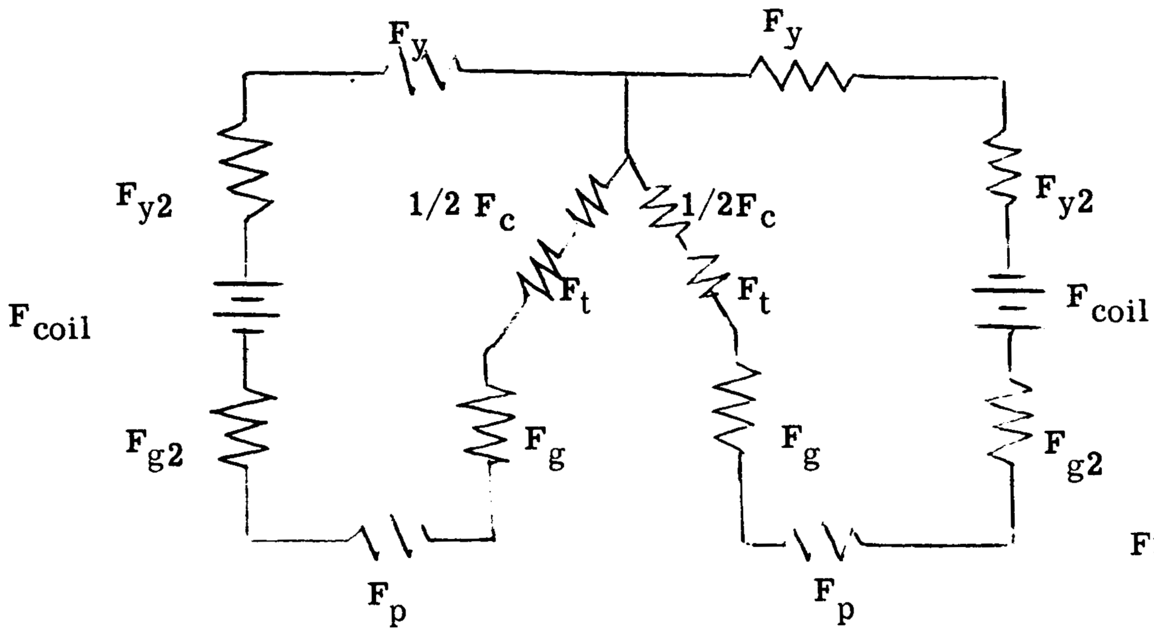


Figure A 33-A

If the stator iron is separated from the housing or yoke by a non-magnetic spacer, the mmf drops can be represented by the following schematic which is for calculating purposes, exactly the same as the circuit for the machine having its back-iron touching the yoke.

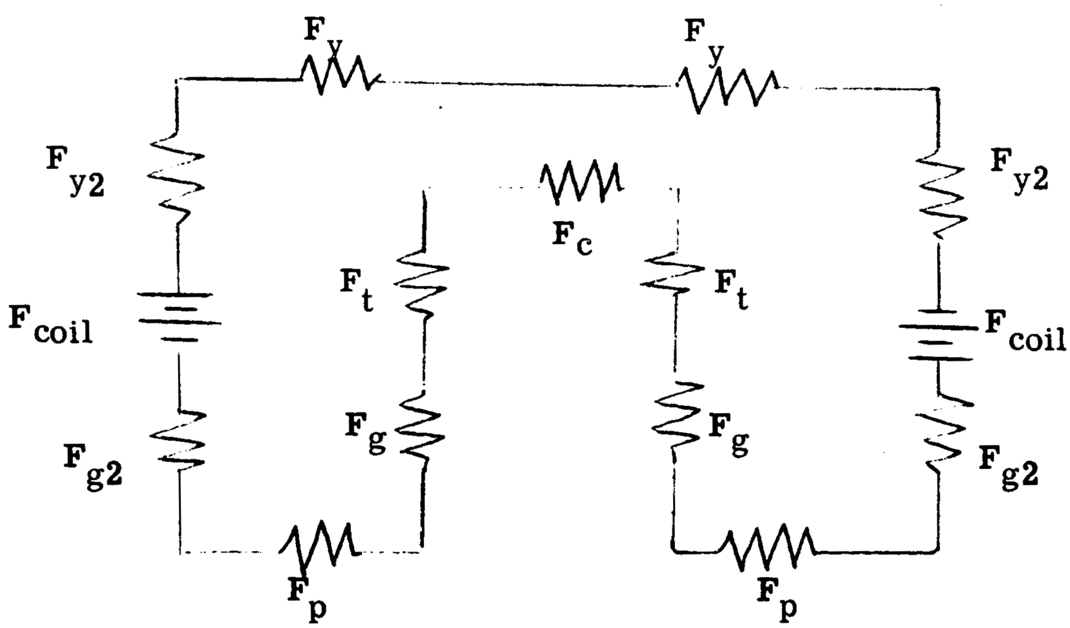
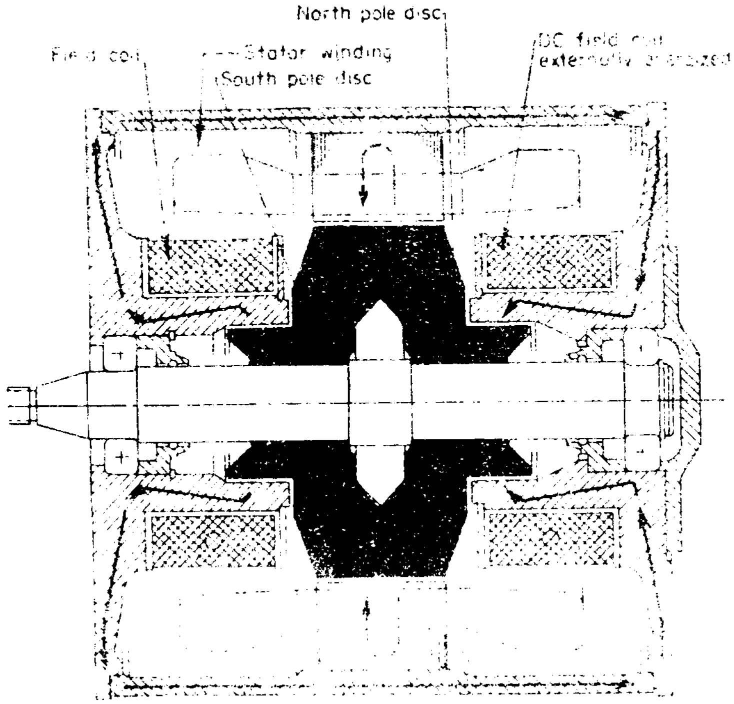
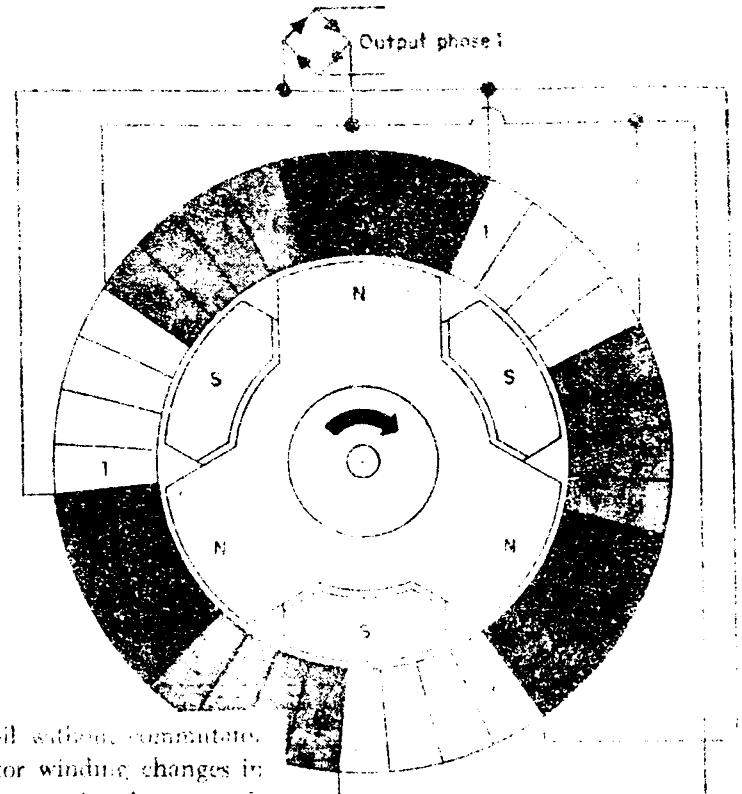


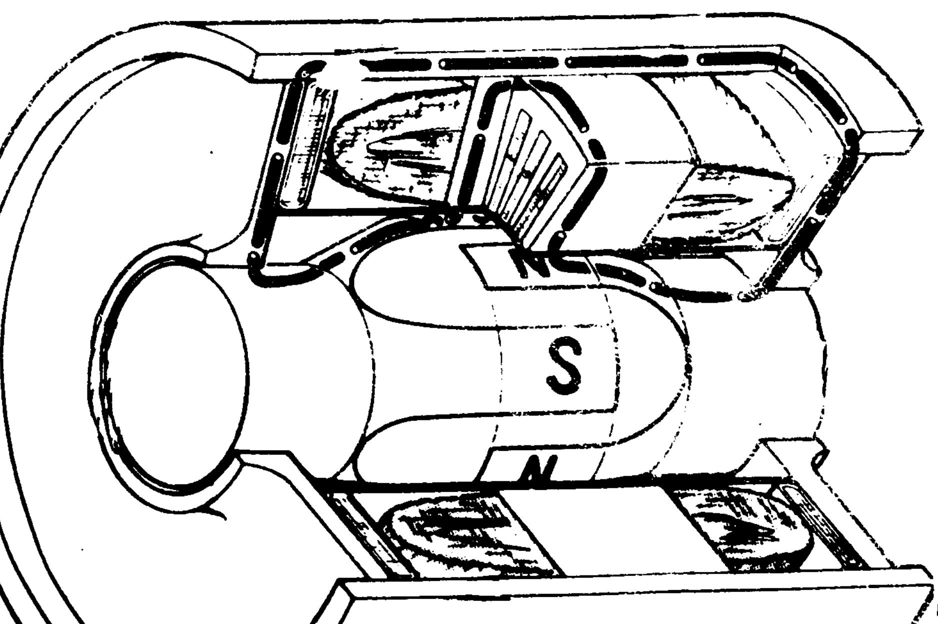
FIGURE A 33 B

TWO VERSIONS OF THE OUTSIDE-COIL LUNDELL





Reversing flux field produces alternating current in a coil without commutators or slip rings. Polarity of the field passing through any stator winding changes in response to the armature pole that is momentarily adjacent to it. Armature is composed of two discs with interlocking poles—all north on one disc and all south on the other. Stationary field windings are inside the ends of the stator windings. There is no moving armature winding. Principle used in a railroad coach alternator by Siemens-Schuckertwerke, Erlangen, Germany.



A PATENT DRAWING FOR AN
OUTSIDE COIL LUNDELL A. C. GENERATOR

(No Model.) 2 Sheets--Sheet 2

L. C. RICE.

DYNAMO ELECTRIC MACHINE.

No. 588,602. Patented Aug. 24, 1897.

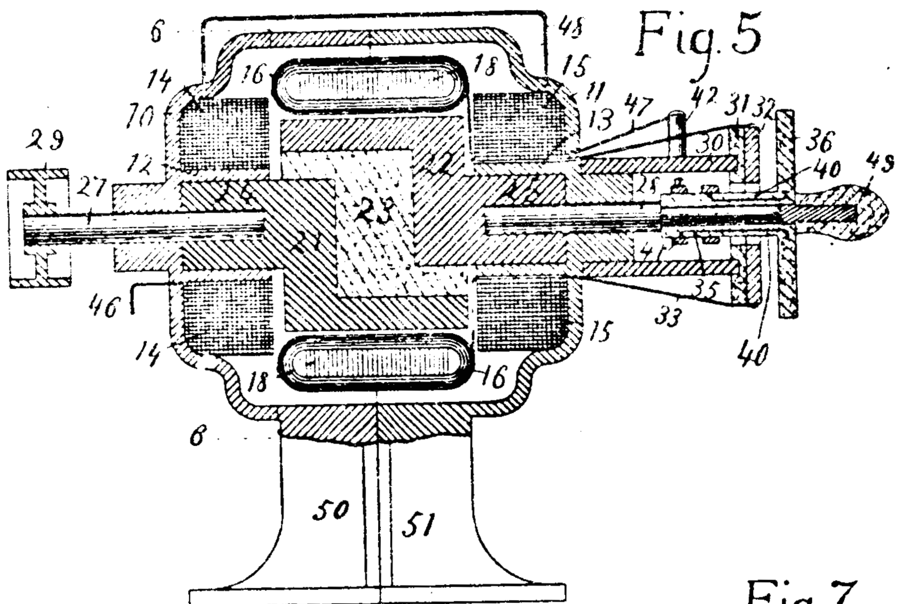


Fig. 5

Fig. 6

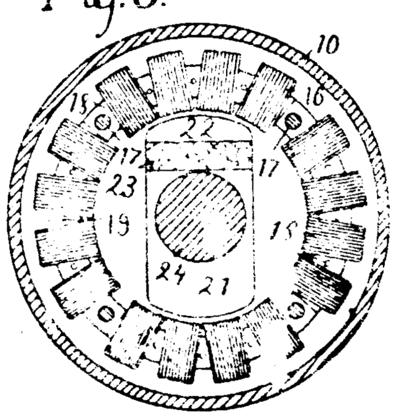


Fig. 7

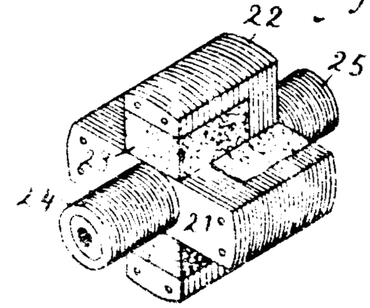
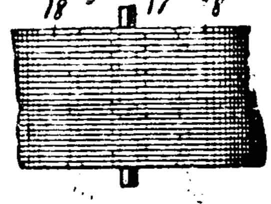


Fig. 8



Witnesses
W. C. Alexander.
E. E. Kimball

Inventor
Lewis C. Rice

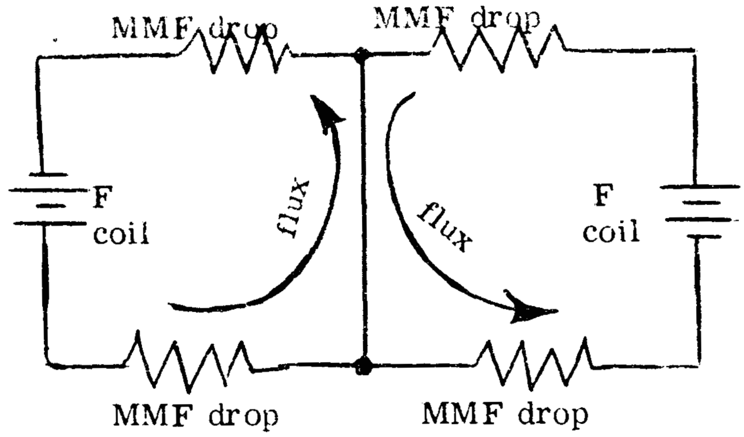
By Attorneys Fowler & Fowler

SINGLE-COIL, OUTSIDE-COIL LUNDELL

The rotor and stator of the single-coil machine are identical to those of the two-coil configuration. Leakage permeances around the stator and coil are different and the flux circuit is different. There can be only one long single loop or circuit for the flux of the single coil machine and there are two series loops for the two-coil machine.

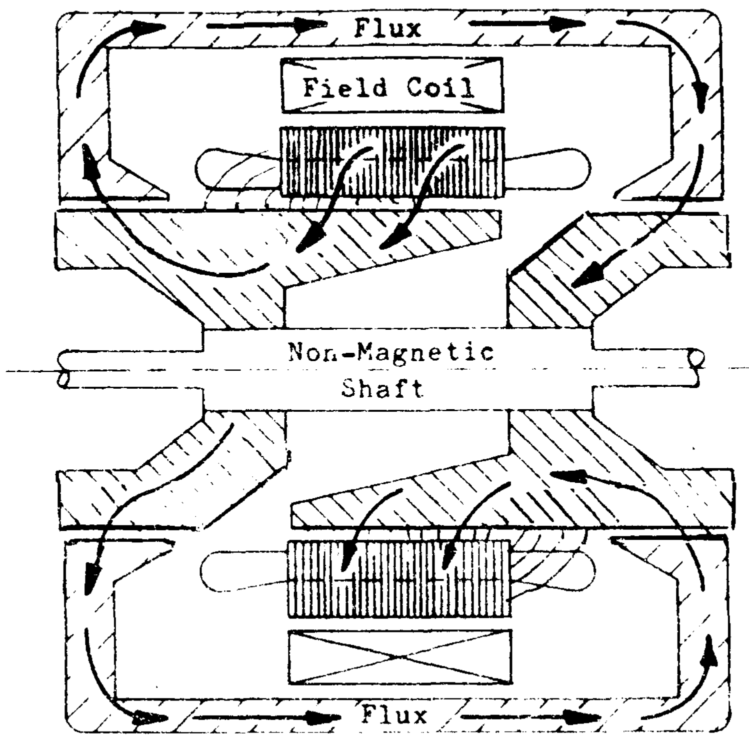
The single outside coil Lundell probably should be used if the generator has only two poles. In the single coil configuration, there is no direct flux circuit from the stator into the yoke and the flux in the air-gap over each pole is more nearly equal. This reduces but does not eliminate the possibility of a rotating couple due to unbalanced pole fluxes.

There are two ways the two-pole Lundell can have an unbalance or a rotating magnetic couple on its rotor. In the two, outside coil Lundell, if the stator is mounted in the magnetic steel housing, there are two possible magnetic paths through the stator. Shown schematically, the two paths look like this -



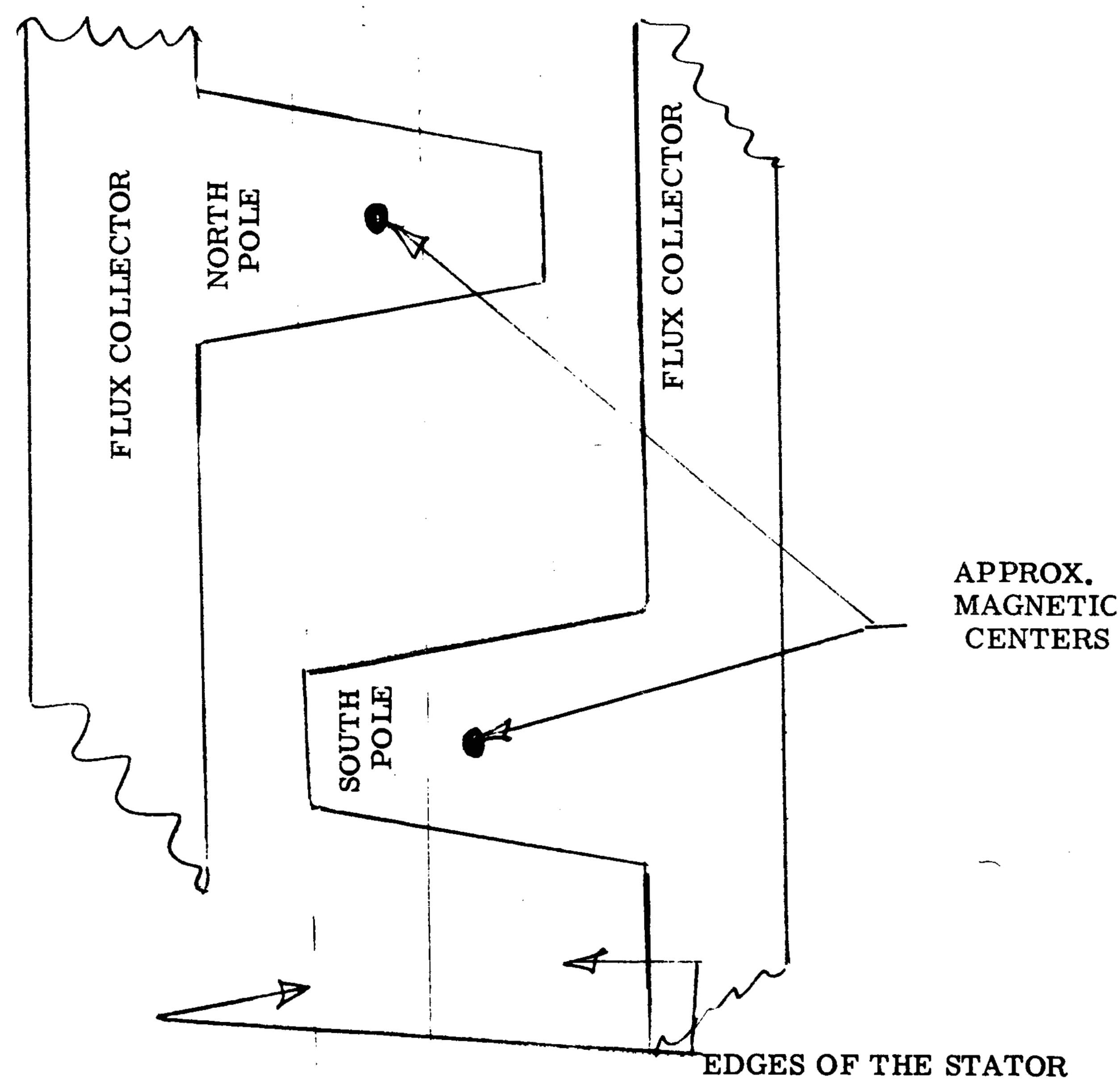
If the two fluxes are equal, the magnetic attraction between each rotor pole and the stator are equal. If the fluxes are different values because of different numbers of coil turns, varying magnetic permeability of yoke and end bells, difference in lengths of the auxiliary air-gaps, etc., one pole will have greater attractive force between it and the stator than the other pole has between it and the stator. This causes a rotating unbalance that increases with an increase in excitation.

If either the two-coil or single-coil, outside-coil Lundell is mounted in the housing with a large air-gap or non-magnetic spacer between the stator back-iron and the housing or yoke, the flux cannot easily cross the non-magnetic space and the flux in the two poles is more certain to be equal. In this case, the possible difficulty with rotor dynamics may be a rotating couple caused by the effective magnetic centers of the two poles being in different planes of rotation.

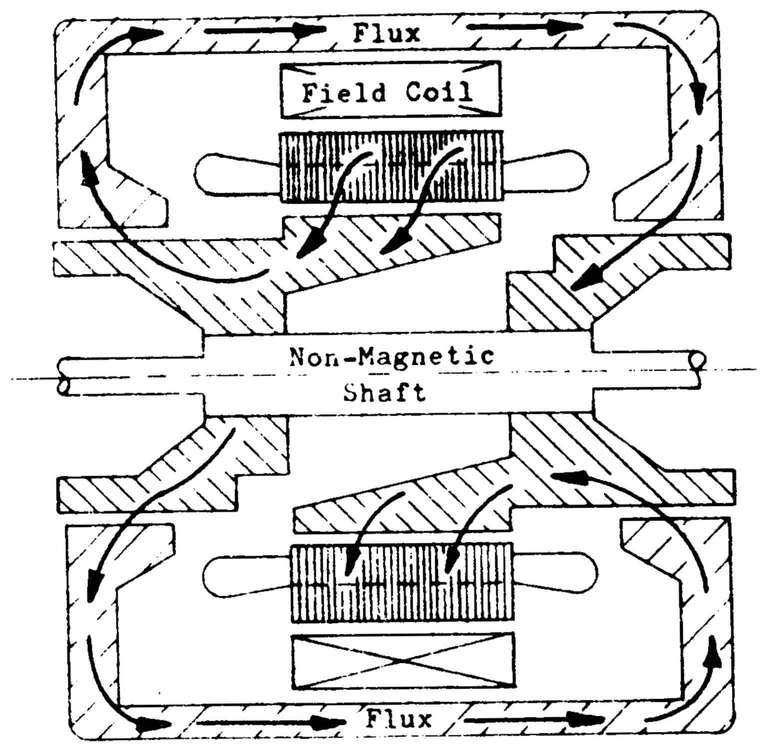


A two-pole Lundell generator with the excitation-coil external to the rotor can be built with the flux collector section of the shaft on the same diameter as the rotor diameter at the pole surface. This configuration causes a maximum amount of fringing flux to enter or leave the stator at the bases of the cantilevered poles and from that cause alone the magnetic center of the pole must shift away from a plane through the center of the stator.

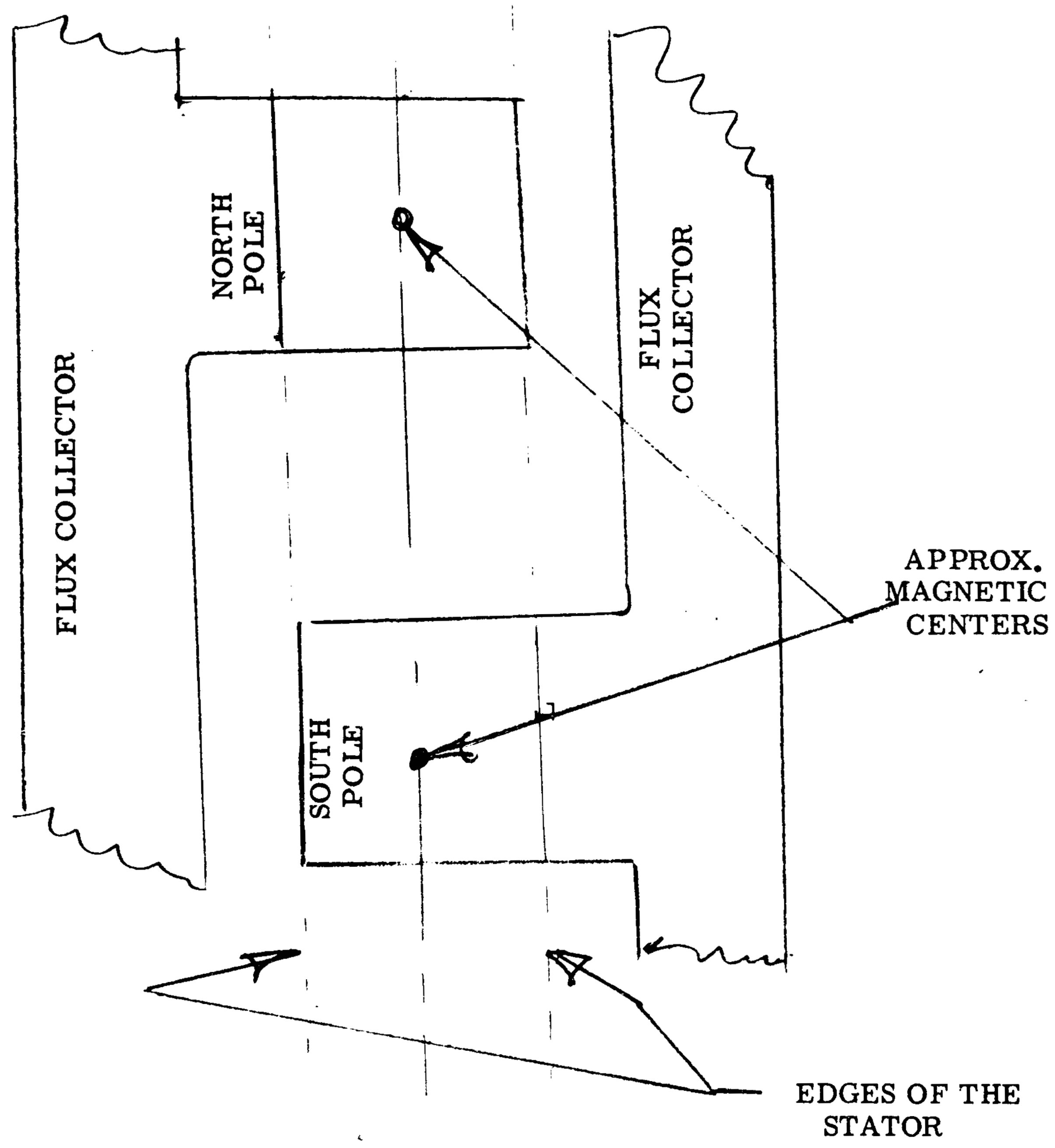
If in addition, the poles are made trapezoidal as is commonly done in Lundell generators, the magnetic center of the pole is shifted away from the center-plane of the stator because of the markedly different amounts of flux passing from the pole to the stator on each side of the centerline of the stator. The combination of these two causes of displaced magnetic centers can cause a large rotating couple that varies with variation in excitation.



If the flux-collector section of the shaft is made appreciably smaller in diameter than the surface of the rotor poles and in addition if the poles are made rectangular in shape, the dynamic unbalance can be made to be small and conceivably can be made as small as desired. Rotating couples in such a case would be eliminated at the expense of increased weight.

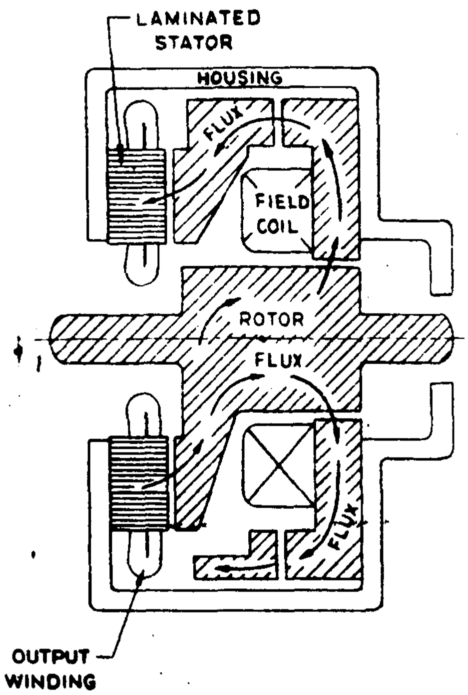


The sketch above shows the step-down shaft in the flux collector region. This reduces fringing flux at the base of the cantilevered pole and reduces the shift of the magnetic center of the pole away from a plane through the stator centerline.



The sketch above shows the two poles made rectangular. The poles can be shaped so that no appreciable shift of the poles magnetic centers will occur.

AXIAL AIR-GAP, LUNDELL TYPE, A. C. GENERATOR



The axial air-gap Lundell a. c. generator with a stationary excitation coil is of recent origin and this type of generator has been tried for several applications. At least one design is being used in production quantities for electrical power in an undersea weapons system.

The original Lundell generator patented by Robert Lundell in 1893 was an axial air-gap generator with the output windings rotating.

The newer brushless, axial air-gap generator has the field structure rotating and the output winding is stationary. The brushes are eliminated through the use of auxiliary air-gaps.

The weight of this machine is approximately the same in small ratings as that of a radial gap Lundell generator of the same rating, speed and frequency. It can be built with two stators and one field coil for maximum output at a given diameter.

The output of any Lundell-type a.c. generator with a rotating pole structure is some function of the stator inside diameter. The equivalent stator diameter for the axial air-gap generator is the square root of the average of the $(OD)^2$ and $(ID)^2$ or $\sqrt{\frac{D^2 + d^2}{2}}$.

If a single-stator axial-gap generator and a radial-gap generator are built with the same KVA, frequency, RPM, air-gap flux density, and stator ampere loading (or the same reactances) the rotor of the disk-type generator will be a minimum of two (2) times the diameter of the radial-gap generator.

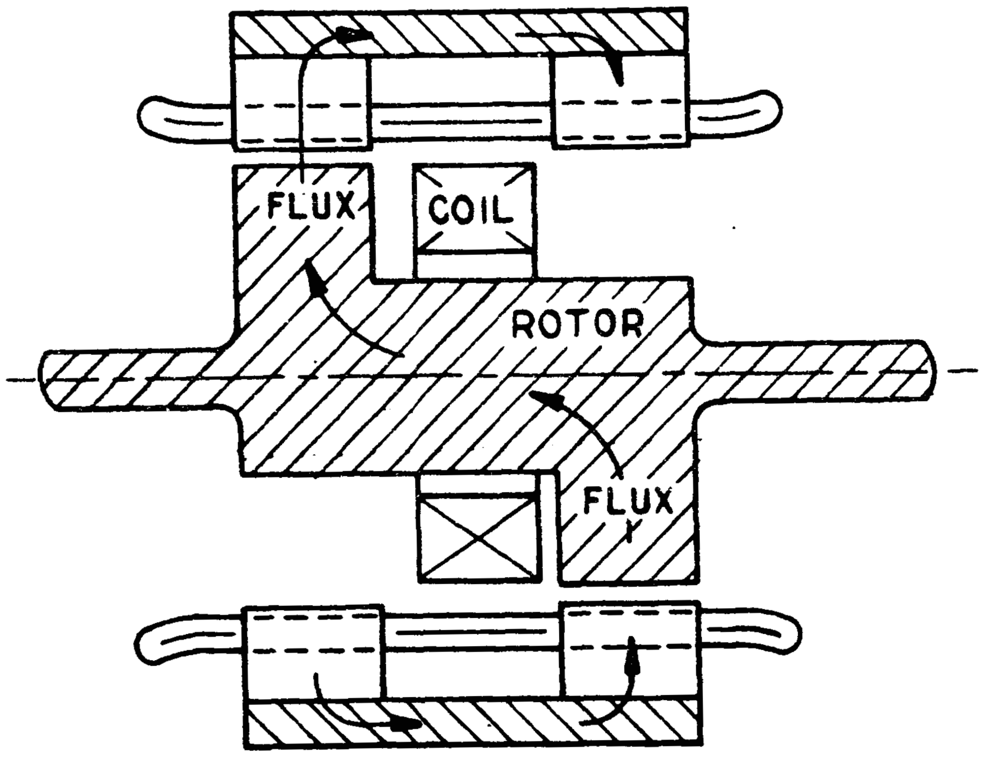
At the same rating and conditions of load, the single-stator axial air-gap machine operates at four (4) times the stress level of the radial-gap machine.

The axial-gap generator is difficult to build and has high rotor flux leakage. In large ratings, the single-stator generator produces high attractive forces between the rotor and stator. These forces are hard to eliminate though they can be reduced by designing the auxiliary gaps to give an opposite attractive force. Because of the attractive force between rotor and stator, the single-stator configuration cannot be used with fluid bearings. The more balanced two-stator design must be used if fluid bearings are necessary. The axial air-gap Lundell A.C. generator may, in small ratings, be useful because of its shape.

HOMOPOLAR INDUCTOR, AC GENERATOR

Before 1900, in the young age of electrical power engineering, many different generator designs were proposed and patented. One of those old designs, widely used since its conception, is described in U. S. Patent No. 499446 issued to William Stanley, Jr. and John F. Kelly in 1893.

The same configuration is now made by every company building homopolar inductor AC generators.



SMALL HOMOPOLAR INDUCTOR GENERATOR

The usual homopolar inductor consists of two identical stators wound with a common winding, a double rotor having all north poles on one end and all south poles on the other end, and a field coil enclosed in the magnetic path formed by the outer shell or yoke, the stators, and the rotor.

When the field coil is excited and the rotor is rotating, unidirectional fields of flux cut the windings of each stator in such a manner that approximately the same voltage is generated in the two stators combined as would be generated in one stator by a single rotor having both the north and south poles of the two ends of the homopolar inductor rotor. In other words, two stators and two rotor ends are electrically and magnetically accomplishing what one stator and its corresponding rotor would do in a conventional salient-pole, synchronous, wound-field generator.

The magnetic flux from the rotor poles passing through each stator section and linking the output windings, is unidirectional and pulsating. Since the magnetic flux never changes direction in a stator and the poles of a rotor section are of one polarity, the generator has been called a homopolar generator (or alike-pole generator).

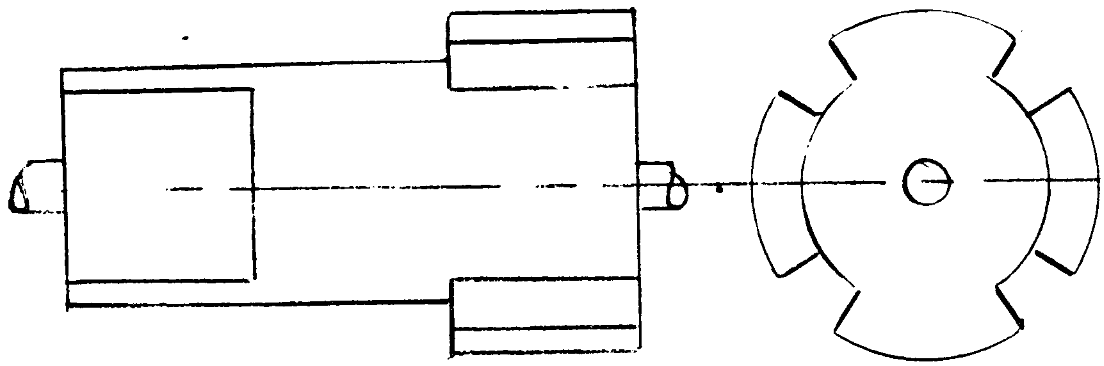
The AC generator known as the homopolar inductor is confused in the literature with a DC generator that is also called a homopolar inductor. The DC generator is called both a unipolar generator and an acyclic generator to distinguish it from the AC machine. A paper given by B. G. Lamme, AIEE Transactions 1912, PP 1811-1835, describes the development problems of a 2000 KW acyclic DC generator. The acyclic generators are of interest for generating the high direct currents needed for pumping liquid metals but are not discussed in this study.

During the seventy odd years of its existence, the homopolar inductor alternator has been used mainly in industrial applications where size and weight were of little consequence. One of its uses has been to supply high frequency electrical power for induction heating of steel products.

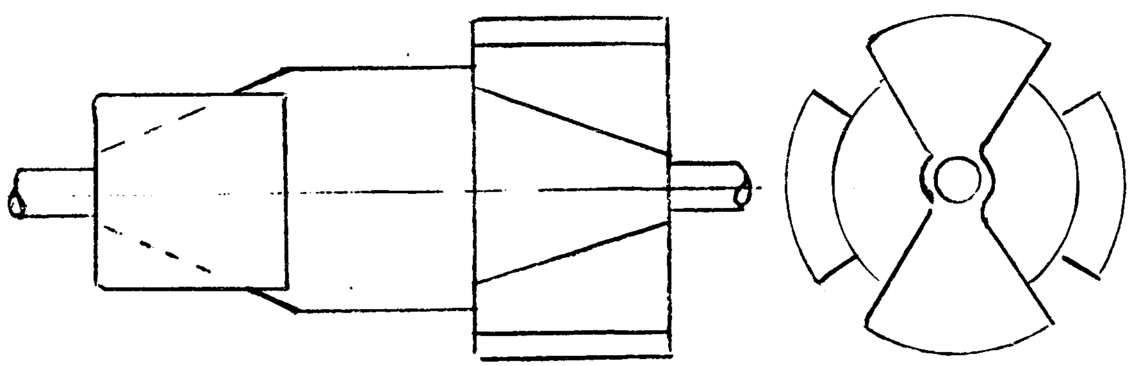
Homopolar inductor designs used in industrial applications have poles, or rotor teeth as they are often called, protruding far out of the shaft so that only a very small amount of unwanted flux passes from the shaft to the stator between the poles of a single polarity (on one end of the stator.)

Recently, the homopolar inductor is being used in airborne and space applications where size and weight are of primary importance. In these applications, the area of the shaft between the two groups of poles of opposite polarities directly limits the maximum output of the machine. In these minimum weight designs, the shaft is the largest diameter practicable and the poles or rotor teeth do not protrude far from the shaft. The unwanted flux passing from the shaft to the stator in the region between poles of like polarity is significant. It is of the order of several percent in a practical, useable design. This unwanted flux generates a voltage opposite to the output voltage in the output windings and reduces the output of the machine.

To get the maximum output from a given rotor diameter, when a small number of poles is used, it is necessary to remove all excess magnetic material from the rotor - to reduce the rotor diameter between adjacent poles or rotor teeth. This treatment is shown by the two following before and after pictures.



View of a conventional four-pole, homopolar inductor rotor with no excess metal removed to reduce the interpolar leakage ϕ_m



The same generator rotor after the excess metal has been removed from between the poles of like polarity.

Reducing the rotor diameter between poles in the manner shown above reduces the unwanted flux between poles and has the effect of increasing the effective pole height.

The output of a homopolar inductor is limited by the diameter of the rotor section between pole-carrying ends (we call the section the Center Shaft Section). Reducing the important interpolar flux leakage (called $\emptyset_m$ in the design manual) reduces the flux carried in the center-shaft at full load and allows the designer to use longer stator stacks. The designer obtains a larger rating from the same rotor diameter and the total generator weight is reduced to a minimum.

When the diameter of the rotor cannot be increased to increase the generator rating, two homopolar inductors can be put together to make a duplex or double homopolar inductor.

Advantages of the homopolar inductor generator for use in space power systems are:

1. It is simple in design and inherently reliable.

2. The homopolar rotor has high strength and can be used for high rotational speeds if bearing problems permit.

3. At lower speeds the rotors can be laminated to remove the output limits imposed by pole-face losses.

Disadvantages of the machine for the same applications are:

1. It is a heavy machine -- the heaviest of all of the AC generators if compared at the same rpm.

2. Stator protection problems are compounded by the two stators when used in a hostile environment.

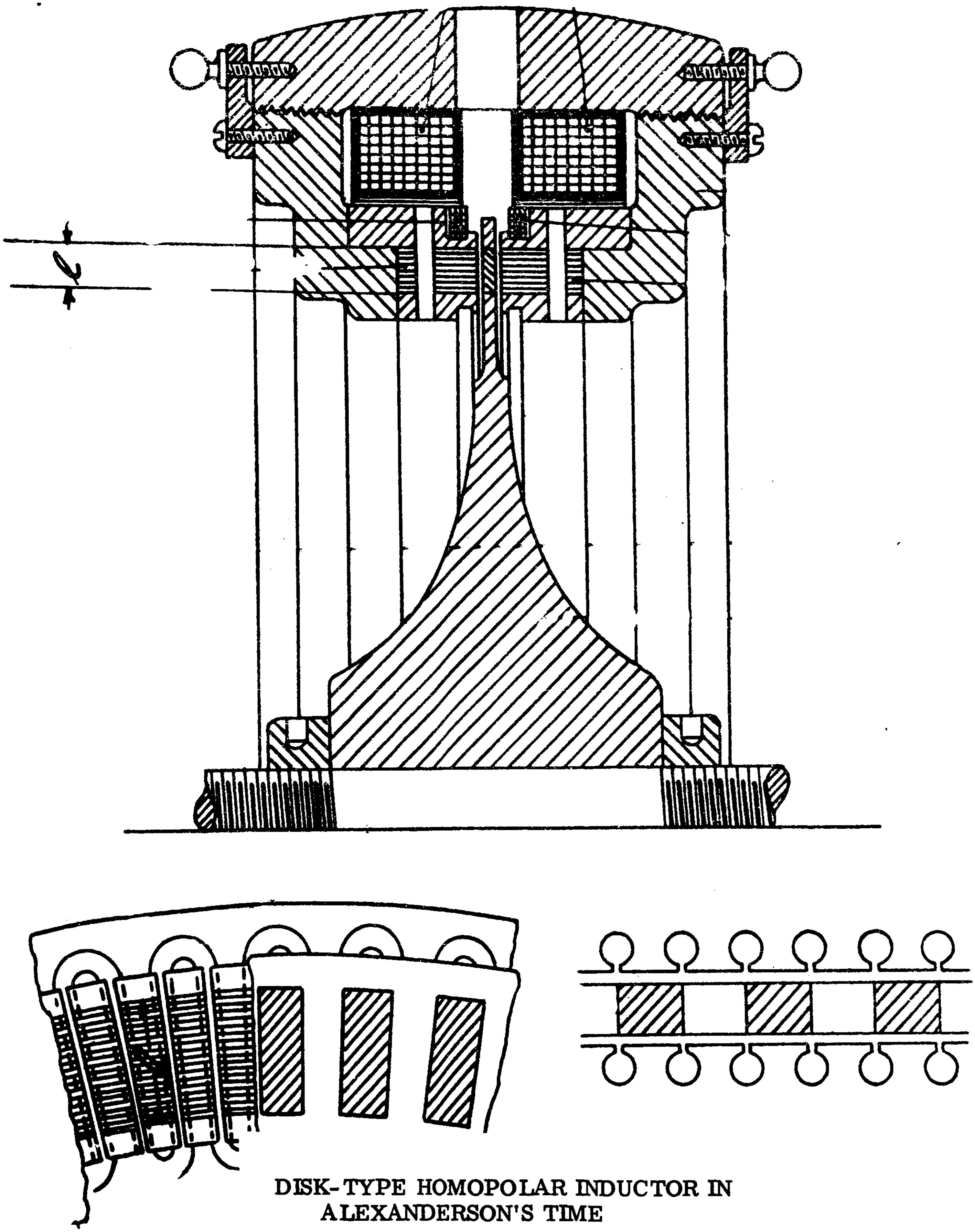
3. The solid pole faces limit the output unless the poles are treated to reduce the pole-face losses.

4. The long, double rotor is sometimes not as stiff as desirable for high-speed applications where fluid or gas bearings are used.

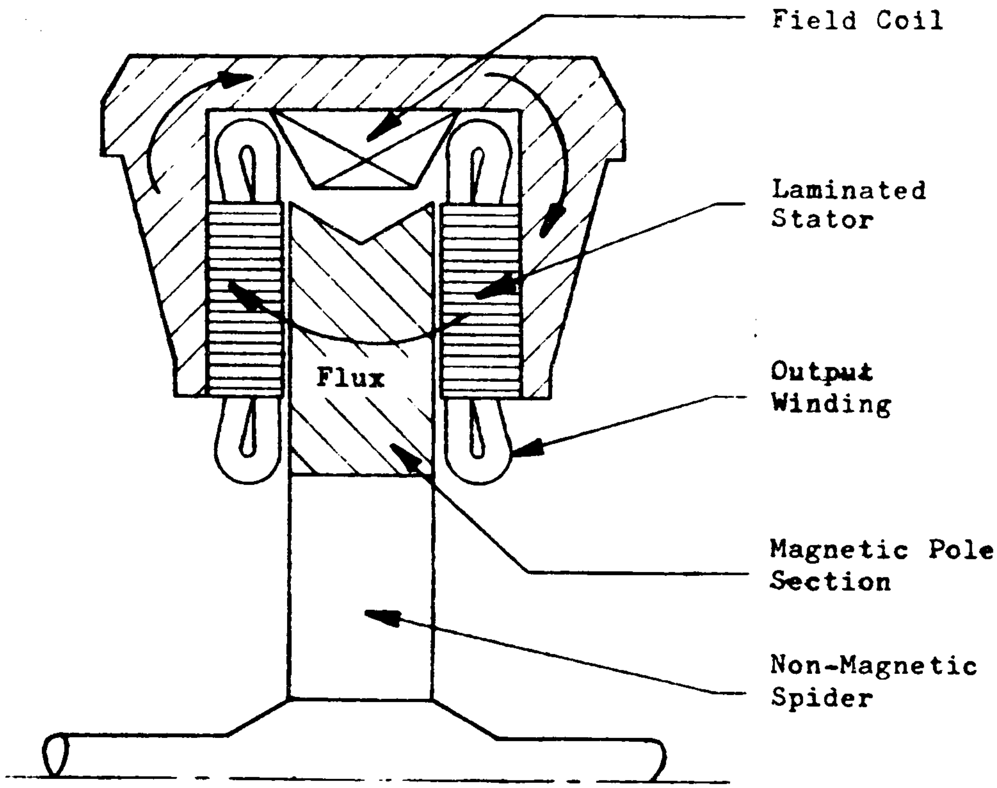
Disk-Type Homopolar Inductor

This inductor generator is described in U. S. Patent No. 1369601 issued February 22, 1921, to E. F. W. Alexanderson.

It is a machine with two disk-type stators facing each other and having a rotor made of alternate magnetic and non-magnetic segments. An excitation coil and iron yoke are located around the outer periphery of the machine, and the flux path is from the yoke, through one stator, into the rotor magnetic segments, into the second stator and then back into the yoke. Mechanical problems make it difficult to maintain equal air-gaps in this machine and the composite rotor cannot be operated at stress levels or speeds comparable to those within the capability of the radial air-gap homopolar inductor. The radial-gap inductor is preferred over the axial-gap inductor both for performance and reliability.



DISK-TYPE HOMOPOLAR INDUCTOR IN
ALEXANDERSON'S TIME



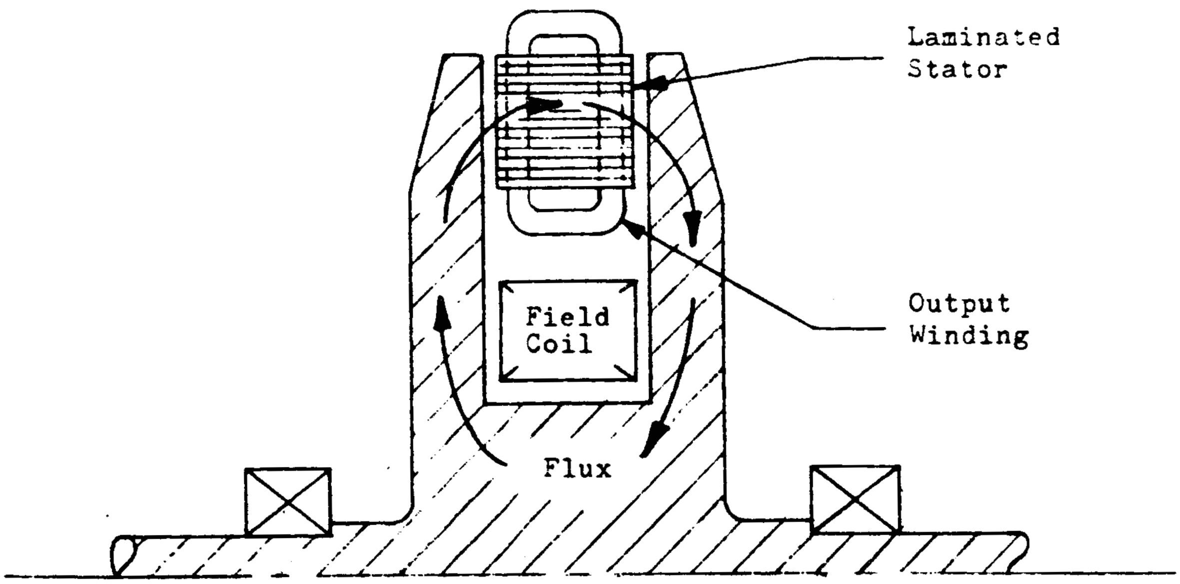
RECENT VERSION OF THE DISK-TYPE HOMOPOLAR INDUCTOR

Another Axial Gap Inductor

This is another disk-type homopolar inductor which is described in U. S. Patent Application No. 3697, dated October 7, 1960.

Similar machines were built and patented by Rolls-Royce Ltd. Derby England, English Pats. 628018, 1947 and 805352, 1955 and by Nikola Tesla U. S. Pat. 447921, 1891.

This would be an acceptable machine electrically but it is difficult to build.

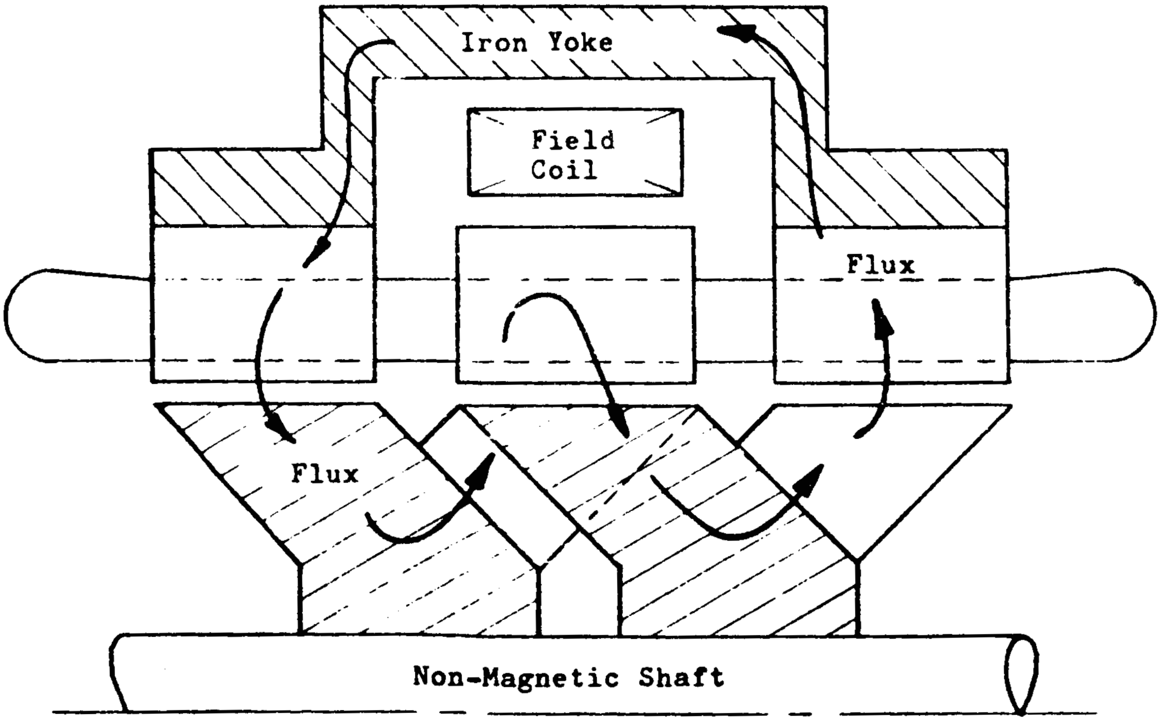


The Homopolar-Inductor Lundell

This machine, consisting of three stators and three rotor sections, was patented in 1938 by Fisher, U. S. Patent No. 2,108,662.

Because the stator length/rotor diameter is definitely limited in both the homopolar generator and the Lundell, no advantage is had by combining the two machines.

This machine has been abandoned and the homopolar inductor or the stationary coil Lundell is usually proposed in its place.



PERMANENT MAGNET GENERATORS

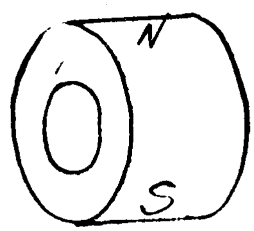
General Discussion

One of the first, if not the first, low voltage A. C. generators ever built was a permanent magnet generator built by M. Hyppolyte Pixii and demonstrated before the Paris Academie des Sciences in 1832. The Hyppolyte generator was a simple axial air gap generator and it used a mechanical commutator to rectify the output. A recent P. M. generator patent portrays the same type of machine and uses rotating axial magnets in the same way.

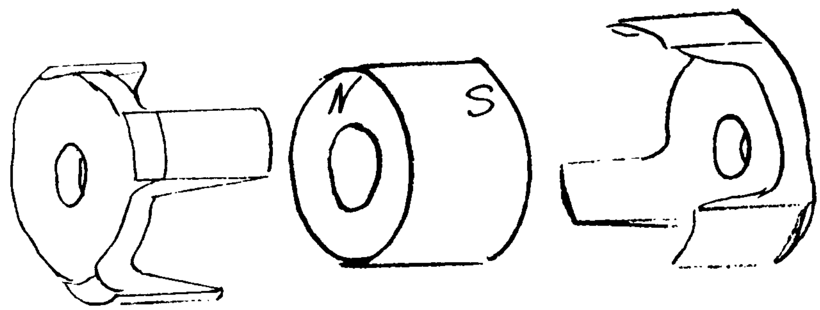
The permanent-magnet generators operate on the same principle as the wound-pole electromagnetic generators. The permanent-magnet replaces the iron pole and exciting coil and furnishes the flux that the iron pole and exciting coil would have furnished.

A permanent-magnet generator can be made in nearly every type of generator known. Some, if not most, of the configurations would be impractical and the most often encountered PM generators are DC generators with commutators, salient pole AC generators with rotating magnets, flux-switch generators with stationary magnets, round rotor or non-salient-pole generators with rotating magnets. The last named generator is usually encountered as a tachometer.

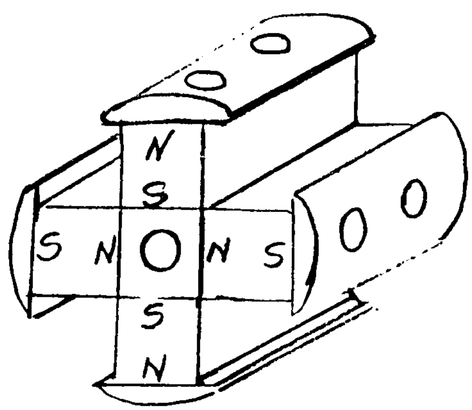
SOME OF THE ROTOR TYPES USED IN A-C PERMANENT - MAGNET GENERATORS WITH RADIAL AIR - GAPS



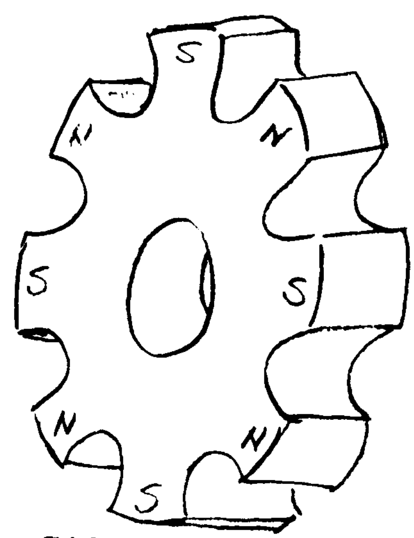
SMOOTH ROTOR



LUNDELL OR CLAW-TYPE ROTOR



BOLTED POLES



CAST POLES

The design manual written for this study and published in the Topical report CR-54320 is for the salient pole generator with rotating magnets.

Induction Generators

The induction generator, also called an asynchronous generator, is an induction motor operating at a negative slip, or operating above synchronous speed. To operate above synchronous speed, the machine must be driven by a prime mover.

An external or auxiliary source must supply the magnetizing current of an induction generator. The induction generator cannot provide reactive power even for its own magnetizing current. The same external or auxiliary capacitive power source must also supply any lagging or reactive power required by the load.

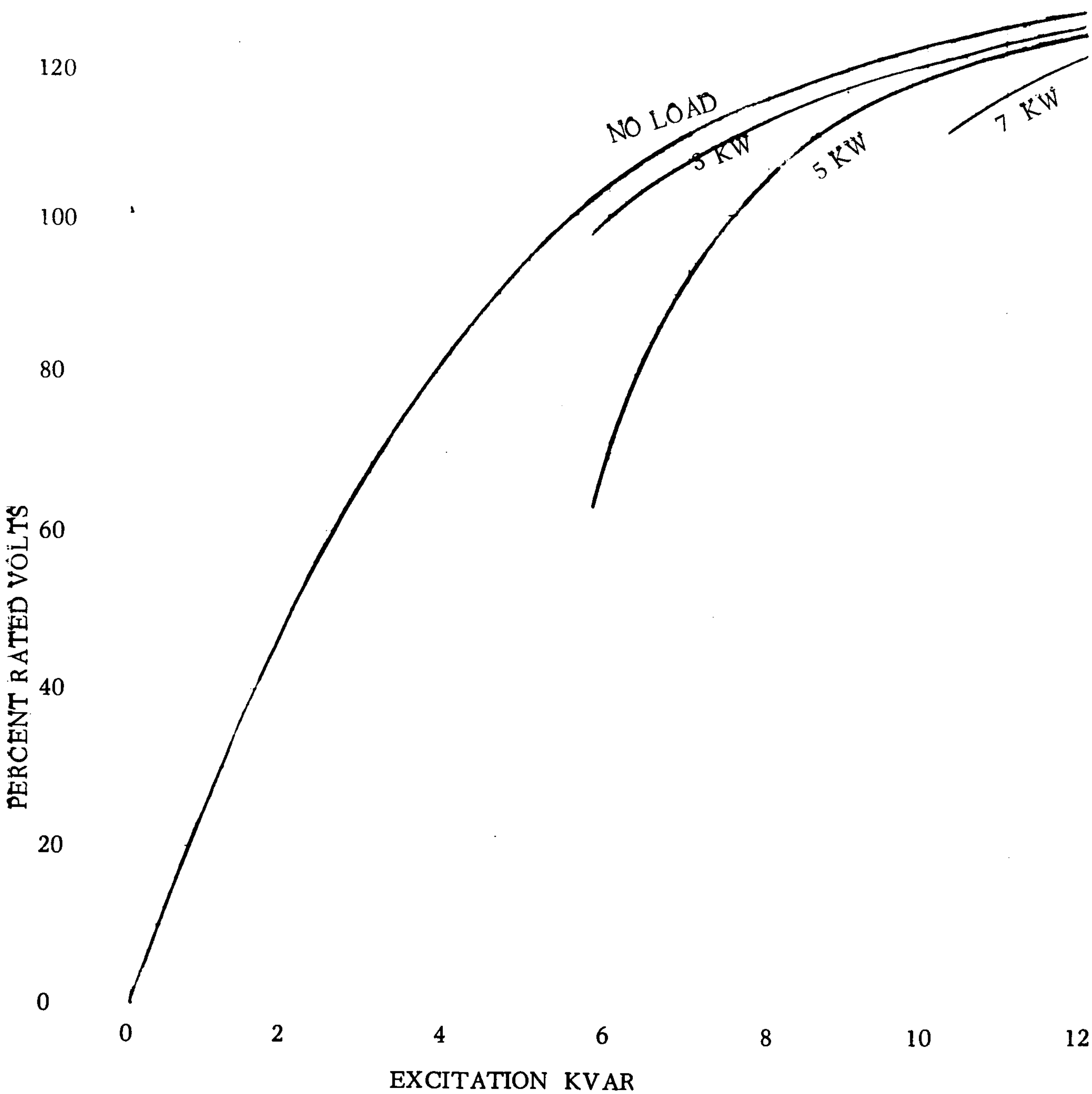
This excitation requirement is an outstanding deficiency of the induction generator because the total capacitive power requirement often exceeds the rating of the generator.

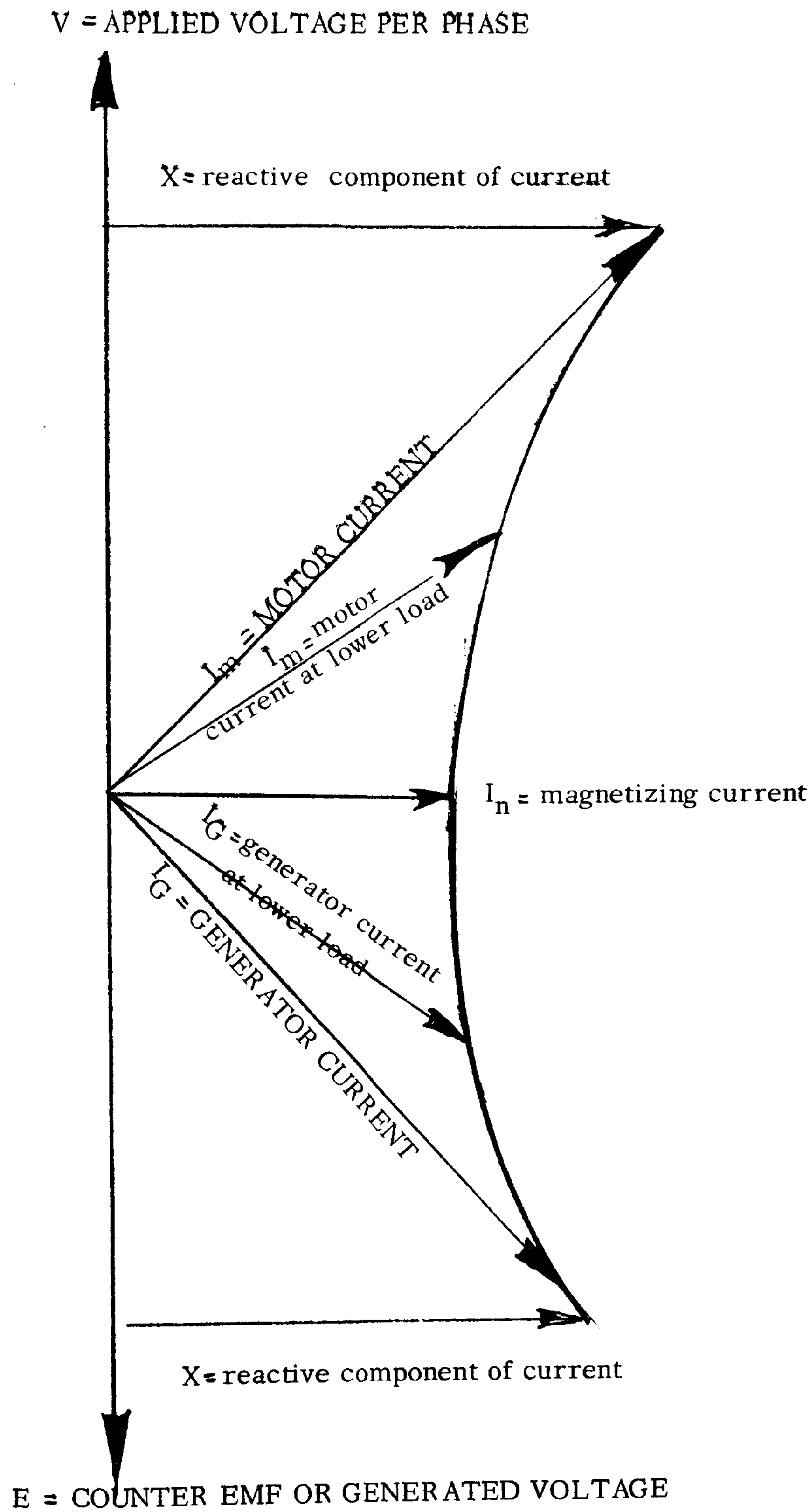
For large induction motors and generators, a normal operating power factor is between .8 and .9 depending in part upon the rpm and the number of poles in the machine.

If the operating power factor of the induction generator is .9 (an unusually high figure), the reactive KVA needed for excitation is then .43 of the induction generator output. In addition, if the load power factor is .8, the reactive power source must supply reactive power equal to .6 of the load KVA rating. Working out the arithmetic shows that the reactive source must supply a total of 0.98 of the load KVA rating. The total requirement of the capacitive source is almost as much, in this case, as the total KVA load requirement. This entire capacitive requirement must be supplied by an external source which would be as large or larger than the generator itself.

Often, when induction generators are proposed, a discussion of excitation requirements is neglected. The following curves show actual machine ratings versus excitation requirements for a small machine that has a worse power factor than the example given above.

CAPACITIVE EXCITATION REQUIREMENT FOR 1.0 POWER FACTOR LOADS ON A SMALL 400 CPS, INDUCTION GENERATOR





REFERENCE: KARAPETOFF "EXPERIMENTAL ELECTRICAL ENGINEERING"
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To control the output voltage of the induction generator, either the prime mover speed or the capacitive excitation must change. Neither of these control methods is pleasant to contemplate and the induction generator is usually only applied on a large system where no controls of any kind are needed for the induction generator or the prime mover (maybe a small waterwheel).

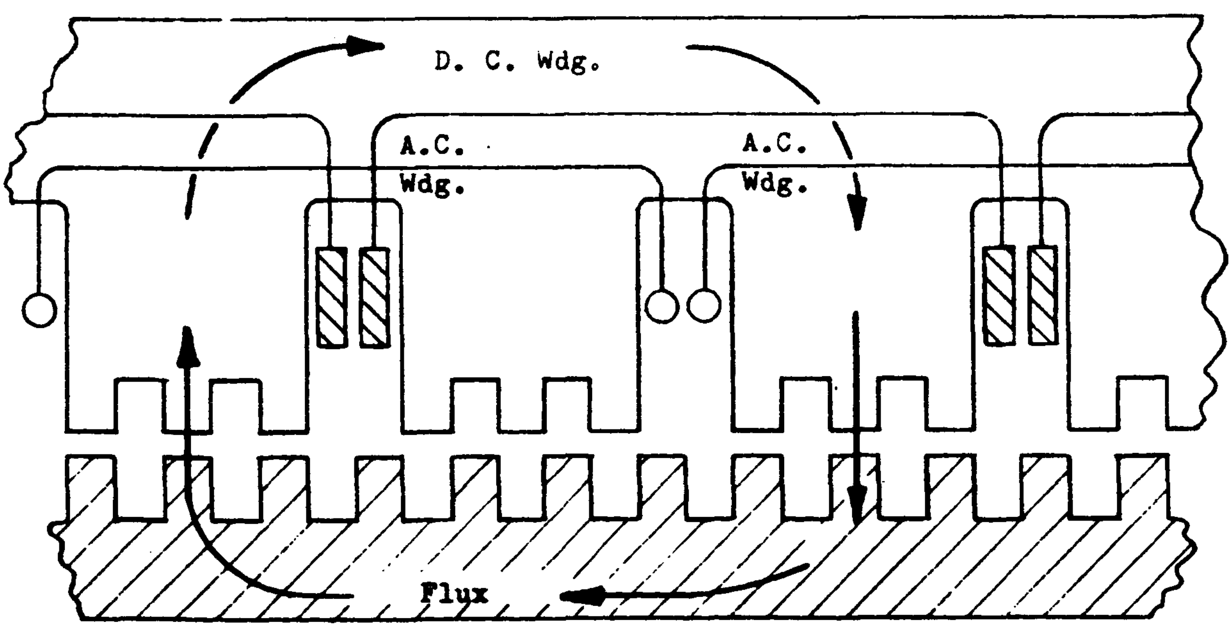
The large system provides the voltage and the frequency control necessary.

Heteropolar Inductor Generator

This machine has a single rotor with teeth similar to the teeth or poles on the homopolar inductor. The field coils are placed in stator slots and the output windings are also placed in stator slots. The two sets of windings and the stator teeth are arranged so that when the rotor moves one tooth pitch, the flux through the a-c winding reverses direction.

One early machine of this type was described in British Patent No. 18027 issued in 1901.

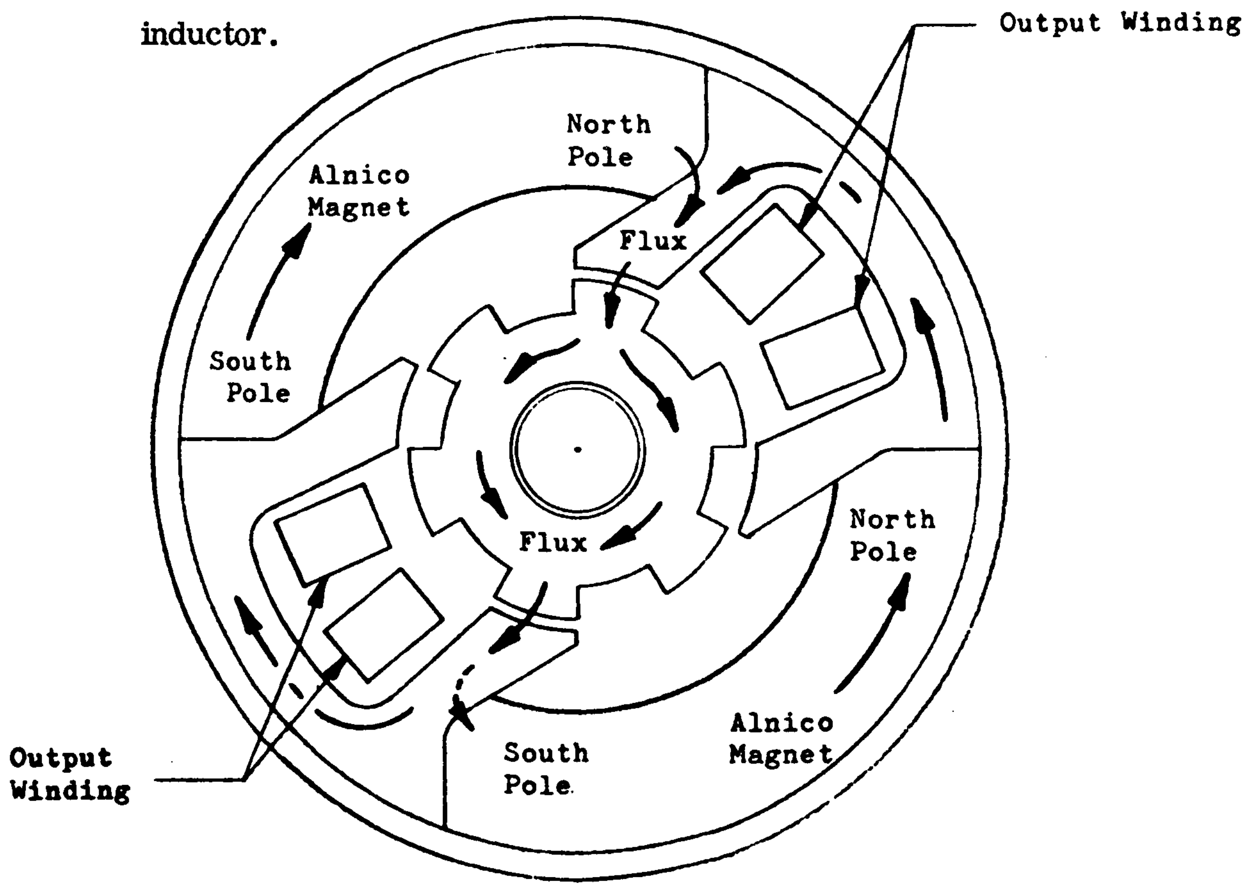
The heteropolar inductor machines can be built with more than one phase but are more commonly designed for single phase operation.



The best application of the heteropolar inductor a-c generator has always been induction heating where fast response is desirable but good wave form is not important.

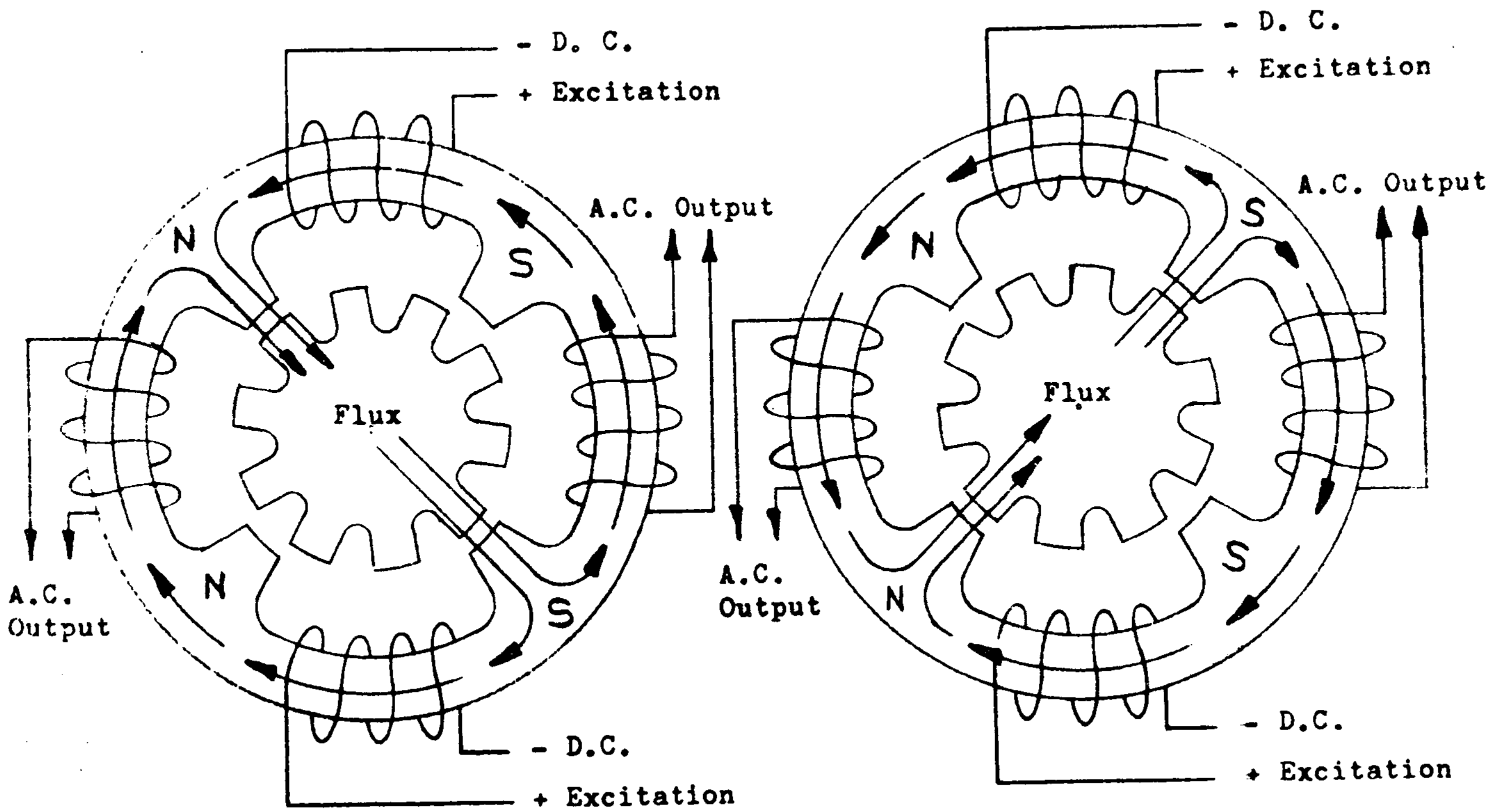
To be able to widely use the heteropolar inductor as an electrical system power supply, it should have a good voltage wave form. Obtaining a good voltage wave from a heteropolar inductor is possible at a specified frequency and load but is not practical to attempt over a range of loads and speeds.

The flux-switch generator is a simple version of the heteropolar inductor.



Electromagnetic Flux-Switch Alternator

The flux switch alternator is a simple version of the heteropolar inductor. It is used only where low outputs are needed and wave form is unimportant.



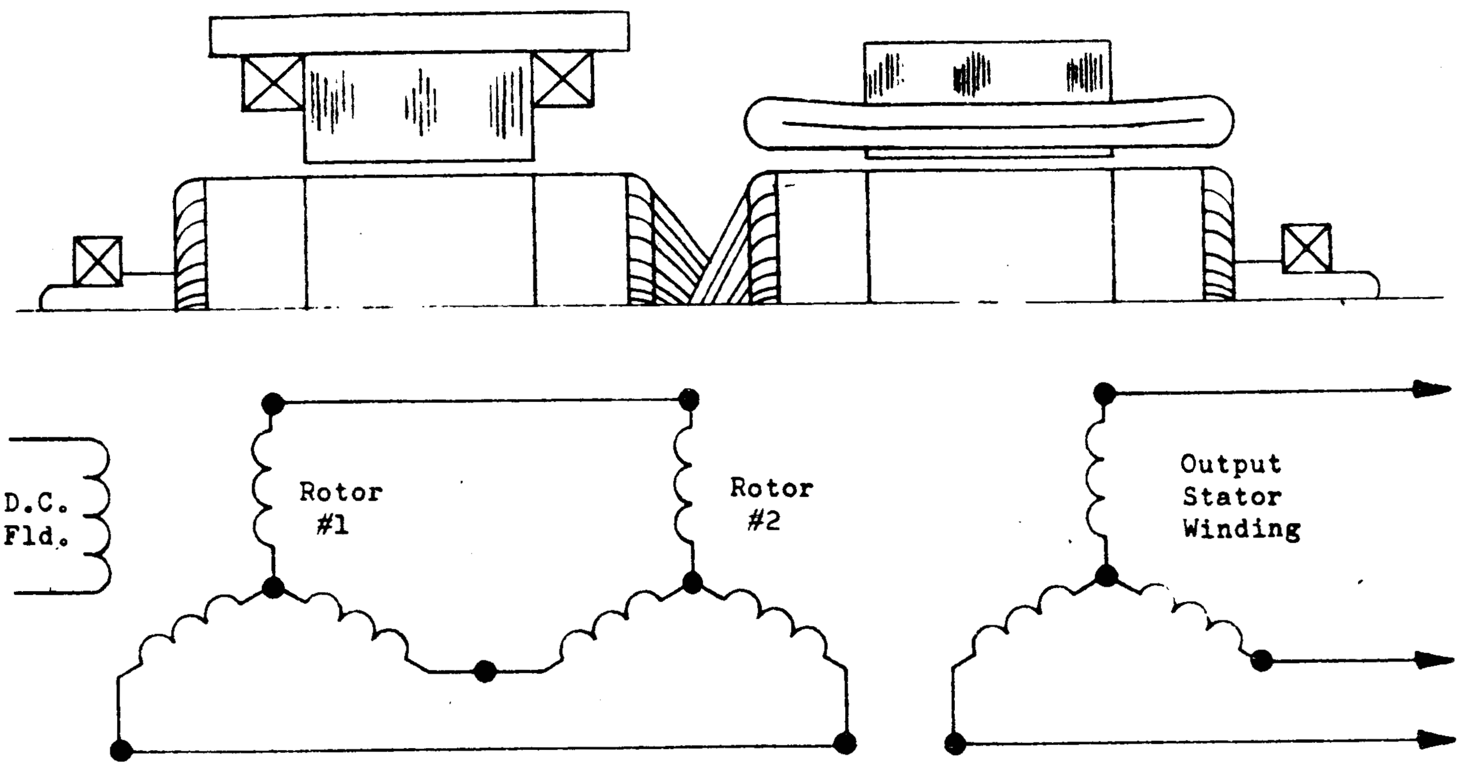
Cascade Generators

Cascade generators can be described as consisting of two generators in series. The rotors of both generators are on a common shaft with the polyphase output windings of the first rotor feeding, with reversed phase sequence, the polyphase windings of the second rotor. The flux wave on the second rotor travels at some multiple of synchronous speed (usually twice), and produces in the output windings of the second machine, a frequency that is the same as if the poles of both machines were combined on one rotor.

The cascade machine can be thought of as a two-stage synchronous generator. Both stages, if the number of poles are equal, will absorb the same shaft power. From a control standpoint, the first stage gain* will be high, of the order of 20 to 50. The second stage gain will be about 2.

The cascade generator, using copper windings in the rotor and requiring transpositions between rotor sections, is limited to about 500^{o} F rotor operating temperature. The rotor is long and in a practical design its critical frequency is low so for high temperatures or high speeds the cascade generator is not a good choice.

*



SCHEMATIC FOR CASCADE GENERATOR

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